

THE INFLUENCE OF DIRECT CYLINDER INJECTION OF
ETHYL ALCOHOL AND WATER ON DETONATION

R. M. DOUGHERTY

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Professor Joseph S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

We herewith submit a thesis entitled "The Influence of Direct Cylinder Injection of Ethyl Alcohol and Water on Detonation." This is in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

ACKNOWLEDGEMENTS

The authors wish to express their grateful appreciation for the assistance willingly rendered by the entire staff of the Sloan Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts. We are particularly indebted to Professor C. F. Taylor, Professor E. S. Taylor, Associate Professor A. R. Rogowski, Assistant Professor W. A. Leary, Assistant Professor P. M. Ku, and Messrs. C. Kano, J. L. Fardy, and E. Gugger for their generous and capable guidance during the course of this investigation.

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I - SUMMARY

Tests were run at the Sloane Laboratory, Massachusetts Institute of Technology, to compare the relative effect of injecting ethyl alcohol and distilled water directly into the cylinder of an internal combustion engine for the purpose of suppressing detonation. The investigation was confined to the cruising range and the following general results were evident:

(1) A marked increase in detonation limited IMEP is realized for alcohol/fuel ratios up to 0.8 with the engine operating at fixed compression ratio, RPM and F/A ratio. For purposes of comparison at a water/fuel ratio of 0.5, a fuel/air ratio of .07, and a compression ratio of 7.0, a 15% increase in detonation limited IMEP is obtained with water injection and an additional 20% boost in detonation limited IMEP may be obtained with alcohol injection.

(2) In all cases it is possible to obtain increasing values of detonation limited IMEP with increasing alcohol/fuel or water/fuel ratios, although the benefit is less pronounced above fluid/fuel ratios about 0.8.

(3) In the region of lower fluid/fuel ratios (up to 0.7) the injection of alcohol increases the indicated thermal efficiency up to 3%, whereas the injection of water has a slight tendency to decrease it. These efficiencies are based on the heating value of the fuel alone.

(4) If operating at a constant detonation limited IMEP, a given compression ratio may be utilized at an appreciably lower alcohol/fuel ratio as compared to the water/fuel ratio required to obtain the same condition. This effect is more pronounced at higher fuel/air ratios and enables the designer to take advantage of the increase in thermal efficiency associated with higher compression ratios.

(5) At a fixed fuel/air ratio and fluid/fuel ratio the detonation limited IMEP varies inversely with the compression ratio.

(6) In going from a fuel/air ratio of .06 and .08 at a fixed compression ratio, the relative effect of enrichening the mixture with fuel is more beneficial towards raising the detonation limited IMEP than is the injection of water; i.e., a given weight of fuel addition to the mixture allows a higher detonation-free IMEP than does the injection of an equal weight of water. The injection of alcohol, however, is slightly more effective than enrichening the fuel/air ratio.

II - INTRODUCTION

The purpose of this investigation is to compare the effects of direct cylinder injection of ethyl alcohol and distilled water as a means of suppressing detonation; these fluids were injected separately and not as a mixture.

To date little work has been done in exploring the field of direct cylinder injection to suppress detonation, as compared to injection into the manifold. However, with the great improvement of cylinder injection equipment in recent years, due to efforts in the line of direct fuel injection, the practicability of injecting an anti-detonating agent directly into the last part of the charge to burn has been increased. Previous work has centered chiefly on the use of water and alcohol injection to extend the allowable maximum power ratings of an engine, whereas this report investigates the increase in allowable cruising IMEP made possible by cylinder injection. For this purpose it was decided to use only unsupercharged inlet pressures, and hence it was necessary to use 73 octane gasoline as fuel, so that detonation could be readily encountered at a compression ratio as low as 6.0. Likewise the practical cruising range of fuel/air ratios from .06 to .08 was chosen, and a currently achievable range of compression ratios from 6.0 to 8.0.

Interest in ethyl alcohol as a fluid to be injected is due largely to its having a heating value in itself, and to its having a

CHAPTER 25

The first part of the chapter is devoted to a discussion of the various methods of determining the relative positions of the stars. This is done by measuring the angles between the lines of sight to the stars, and by comparing these angles with the angles which would be observed if the stars were in the same position. The second part of the chapter is devoted to a discussion of the various methods of determining the absolute positions of the stars. This is done by measuring the distances to the stars, and by comparing these distances with the distances which would be observed if the stars were in the same position. The third part of the chapter is devoted to a discussion of the various methods of determining the proper motions of the stars. This is done by measuring the changes in the positions of the stars over a long period of time, and by comparing these changes with the changes which would be observed if the stars were in the same position. The fourth part of the chapter is devoted to a discussion of the various methods of determining the radial velocities of the stars. This is done by measuring the Doppler shift of the spectral lines of the stars, and by comparing these shifts with the shifts which would be observed if the stars were in the same position. The fifth part of the chapter is devoted to a discussion of the various methods of determining the transverse velocities of the stars. This is done by measuring the proper motions of the stars, and by comparing these proper motions with the proper motions which would be observed if the stars were in the same position. The sixth part of the chapter is devoted to a discussion of the various methods of determining the total velocities of the stars. This is done by combining the radial and transverse velocities of the stars, and by comparing these total velocities with the total velocities which would be observed if the stars were in the same position. The seventh part of the chapter is devoted to a discussion of the various methods of determining the masses of the stars. This is done by measuring the gravitational effects of the stars on other stars, and by comparing these effects with the effects which would be observed if the stars were in the same position. The eighth part of the chapter is devoted to a discussion of the various methods of determining the ages of the stars. This is done by measuring the chemical composition of the stars, and by comparing this composition with the composition which would be observed if the stars were in the same position. The ninth part of the chapter is devoted to a discussion of the various methods of determining the distances to the stars. This is done by measuring the parallax of the stars, and by comparing this parallax with the parallax which would be observed if the stars were in the same position. The tenth part of the chapter is devoted to a discussion of the various methods of determining the positions of the stars. This is done by measuring the angles between the lines of sight to the stars, and by comparing these angles with the angles which would be observed if the stars were in the same position.

high anti-knock rating when used as a primary fuel. Interest in water stems from its universal availability and its high latent heat of vaporization.

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TO THE EDITOR OF THE JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF CHICAGO
RE: [Illegible Title]
[Illegible text block containing details of the study, including authors, dates, and findings. The text is too faint to transcribe accurately.]

III - DESCRIPTION OF APPARATUS

A schematic arrangement of the entire apparatus appears in Figure 19.

The engine used in this investigation is a standard CFR test engine made by the Waukesha Motor Company, Waukesha, Wisconsin; it has a displacement volume of 37.33 cu. in., with a 3.25 in. bore and a 4.50 in. stroke.

The induction system consists of an inlet from either the atmosphere or a supercharged pressure line, a .515 Foxboro orifice to measure the air flow, a surge tank, mixing tank with steam jacket heater, a throttle valve, and necessary piping. The surge tank is provided to dampen any oscillations in the line due to the intermittent pumping action of the engine, and the mixing tank is designed to thoroughly vaporize the fuel and create a uniform mixture. The mass flow of air is measured by a differential water manometer placed across the orifice, and fuel is injected under 23 psi pressure into the top of the mixing tank; its mass rate of flow is measured by means of a Fischer & Porter rotometer. Inlet pressure is measured by a differential mercury manometer, one leg of which is vented to the atmosphere and the other to the mixing tank, while inlet temperature is measured by a mercury bulb thermometer inserted in the inlet manifold. The above system enables accurate determination and control of inlet mixture conditions.

The engine speed is controlled by varying the field resistance in a D.C. dynamometer (see Figure 20), which is run directly from the engine crankshaft. A rough indication of the speed may be read on a tachometer driven by a flexible cable, and the precise engine RPM may be set for integral multiples of 100 by a stroboscope flashing with line frequency (60 cps) upon the fly-wheel, which has 36 radial lines inscribed; under stroboscopic light these lines appear stationary when the engine is running at an integral multiple of 100 RPM.

The dynamometer has a torque arm attached to its field casing, and the torque arm actuates a piston; this latter transmits hydraulic pressure through a medium of 50% SAE 20 oil and 50% kerosene to the bottom of a column of mercury, the height of which above or below a fixed zero setting can be converted to BMEP or FMEP respectively.

The cylinder jacket temperature is controlled by varying the rate of flow of cooling water through the jacket condenser. Likewise the exhaust jacket is kept cool by the continual flow of water. Both steam and water may be fed to the oil temperature control jacket so as to maintain the oil temperature within narrow limits.

The special equipment used in this investigation consists of an American Bosch single piston, positive displacement injection pump number APE 1B 70P 300 3 X58201 (see Figure 16). With increasing

volume flow this pump advances the initial angle of injection, while the final angle remains constant for all flow rates. In conjunction with this pump a Bendix injection nozzle, number 135026, was inserted in the cylinder opposite the spark plug; it is an early experimental model of which only 30 were made, but it furnished satisfactory spray characteristics and differs but slightly from current production models. The nozzle release pressure, chosen as 500 psi to give the best spray, may readily be set by adjusting and securing the spring tension within the nozzle. The pump will develop up to 20,000 psi pressure, so that there is an ample margin of pressure to ensure nozzle ejection. A pressure head of 6 feet of water feeds the pump from a float chamber employed to keep this head constant. Volume flow of fluid through the pump is controlled by means of a micrometer adjustment on the pump housing; this flow is measured by a rotometer located between the float chamber and the pump, and a thermometer is set in the outlet from the rotometer to read the fluid temperature. The arrangement is shown in Figure 18.

A magnetic dp/dt pick-up is inserted into the cylinder in one of the extra spark plug holes, and the voltage signal from the pick-up is fed to a cathode ray oscilloscope to form a characteristic pattern on the screen. When a blip, due to a very rapid change of pressure in the cylinder, appears on the characteristic screen pattern, it is an indication of incipient detonation. This is a more accurate method of

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determining the point of incipient detonation than the magnetostriction or bouncing pin methods.

IV - PRELIMINARY PROCEDURE

The following preliminary operations were necessary to set up the apparatus in order to obtain the desired test data.

First a manometer board (Figure 17) was constructed to measure inlet pressure, static pressure drop across the air intake orifice, exhaust pressure, and brake load. Secondly there had to be constructed a water and alcohol feed system, consisting of a 3 gallon bottle and float chamber suspended from an overhead beam so as to provide a steady 6 foot gravity feed to the injection pump. This system is shown in Figure 17.

The fuel rotometer was calibrated at a fuel temperature of 78°F by using a standard calibration set, which enables the accurate determination of a time interval during which a given mass of fluid flows through the rotometer; from this information the rate of flow may be calculated, corresponding to the observed scale reading on the rotometer. In a like manner a second rotometer was calibrated separately for both water and alcohol, and in the case of water the calibration was run at 3 different temperatures by causing the water to flow through a heat exchanger prior to entering the rotometer. This latter showed that a change in temperature of 4°F caused an error in mass flow of slightly less than 4%, and throughout the later test runs the fluid temperatures were observed and found to vary less than 2°F from the calibration temperature of 77°F; this was due to the fact that

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the fluid was allowed to achieve room temperature before being used, and room temperature varied within a narrow range. In subsequent test runs interpolation for temperature was employed when necessary.

A great deal of difficulty was experienced in determining the best combination of Bosch injection pump and injection nozzle. The spray from the nozzle was observed by means of a stroboscope connected to the set of ordinarily used breaker points, which fire every other revolution of the crankshaft; since the pump is driven directly by the camshaft the stroboscope frequency was identical to the frequency of nozzle ejection, and hence the spray appeared stationary when viewed under stroboscopic light. The first pump that was installed produced a constant initial angle of injection and variable final angle, as the volume flow through the pump was changed, but this pump gave an intermittent spray and had to be abandoned in favor of a newer pump, which had the characteristic of producing a variable initial and fixed final angle of injection. The latter pump provided a regular spray and was tested with several types of injection nozzles at various spring tension loadings, which were adjusted by a compression nut in the nozzle and checked for release pressure in a hand operated hydraulic pump with a bourdon tube gage attached. A Bendix injection nozzle with spring loading of 500 psi was finally selected as giving the most desirable spray. The tubing between the

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pump and nozzle was made as short as possible and with a minimum number of bends; in addition the system was frequently and thoroughly bled of air by means of 2 bleed jets on the pump housing and by loosening the tube joint at the pump. Care was taken to make certain that the injection occurred on the compression stroke by observing under stroboscopic light the opening and closing of the inlet valve.

The effect on initial injection angle of varying the mass flow through the pump was determined by observing the spray under stroboscopic light flashing at half crankshaft frequency; the timing of the stroboscope flashes was varied by rotating the breaker point housing until the spray was at the point of disappearing up into the nozzle, thus indicating the start of nozzle ejections; then the stroboscope was made to illuminate the spark disc and indicate the angle of initial injection as that at which the top center mark appeared on the protractor scale around the spark disc. In a similar manner the angle of final injection was determined and found to be invariant with volume flow, whereas the angle of initial injection advanced in a linear fashion with increased flow rate, as shown in Figure 9. The optimum coupling angle between pump and camshaft was determined by making runs of detonation limited IMEP vs. water/fuel ratio at 3 different coupling angles; the optimum angle was that giving the highest limiting IMEP, as shown in Figure 10.

In order to test the induction system for leaks, a gage pres-

sure of 10 psi was applied and a soapy solution painted on all joints; a few minor leaks were evident and were stopped by painting the defective joint with glyptol. As a final check on the induction system a run was made of brake load vs. F/A ratio; the peak occurred at $F/A=.075$, thus constituting a satisfactory final check.

The micrometer for setting the compression ratio was checked by running the engine until normal operating temperatures were reached and then, with the piston on top center, measuring the weight of distilled water required to fill the cylinder up to the thread corresponding to the depth of the injection nozzle; the volume corresponding to this weight of water is equal to the clearance volume, which was checked against the correct value as taken from a table of standard CFR clearance volumes vs. micrometer setting. The final check on the engine consisted of setting the correct valve clearances and spark plug gap.

On the 1st of January, 1880, the first of the new buildings was begun. The first
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V - OPERATING PROCEDURE

The standard starting procedure (appendix) was used to start the engine which was then allowed to warm up for at least an hour, after which time equilibrium conditions had become established. During the warm-up period the following operating variables were set at their prearranged values: inlet temperature 140°F, oil temperature 140°F, cylinder jacket temperature 210°F, and engine speed 1300 RPM.

Since the Bosch injection pump was designed for use with diesel oil rather than alcohol or water, an auxiliary feed of diesel oil was supplied to the pump during the above warm-up period, thus providing lubrication for the finely lapped piston. In addition, diesel fluid was circulated through the pump after every hour of operation on alcohol or water, as well as at the conclusion of each day's runs.

Following the warm-up period the injection pump was shut off, and the sylphon bellows, which dampen the oscillations due to intermittent pumping and produce a steady flow of fluid through the rotometer, were drained of diesel oil and filled with alcohol or water as desired. In this operation care was taken that the bellows were not allowed to expand too rapidly and cause a flow rate high enough so as to cause air to get into the system at the float chamber. Then the pump was set at a moderate flow and time allowed for all diesel oil to

be flushed through the injection system; during this period the pump was thoroughly bled of any air that might have been in the lines or pump. The satisfactory performance of the entire injection system was manifested by a steady rotometer reading.

When the desired compression ratio had been set, the following sequence of operations proved to be most efficacious and was used on all but the first few runs: while injecting excess fluid to prevent detonation, the throttle was fully opened so that inlet pressure was slightly less than atmospheric; then the fuel flow was adjusted to give the desired F/A ratio, and after allowing several minutes for the mixture to become adjusted, the amount of injected anti-knock fluid was gradually reduced until incipient detonation was indicated on the cathode ray oscilloscope. After recording all data for the run, the inlet pressure was decreased to a predetermined value and the fuel flow again adjusted to maintain the same F/A ratio; the quantity of fluid was then decreased until a second point of incipient detonation was reached, and data was recorded. In a like manner points of incipient detonation were determined until the flow of injected fluid became zero, and then the process was repeated at a different value of F/A ratio or compression ratio.

VI - DISCUSSION

In order to best show the relative effectiveness of injecting 95% ethyl alcohol and water directly into the cylinder for the purpose of suppressing detonation, Figures 1, 2 and 3 picture detonation limited IMEP plotted against alcohol/fuel or water/fuel ratio required to enable the use of a given detonation-free IMEP; these curves are for each of three compression ratios, 6, 7 and 8. The primary variables on each curve are inlet pressure and alcohol or water flow rate, while a secondary variable is the initial injection angle which advances with increasing fluid flow due to the inherent characteristic of the injection pump; all other variables, F/A ratio, compression ratio, spark advance, RPM, inlet temperature, and jacket temperature are held constant along a given curve. Proceeding up one of these curves from left to right successive points represent higher inlet pressures, and give the maximum detonation-free IMEP that can be obtained using the corresponding flow of anti-detonating fluid. The spread of points on all these curves is well within experimental limits, and several check runs were made to substantiate data taken on a previous day, thus indicating satisfactory control throughout the tests.

These figures show a distinctive S-curve that is representative of the alcohol in suppressing detonation; this trend is especially evident at compression ratios of 7 and 8, while at a compression ratio of 6 the use of unsupercharged inlet pressures limited the

CHAPTER IV

The first of the four main parts of the book is devoted to a general survey of the history of the English language. It begins with a chapter on the prehistoric period, and then proceeds to the Anglo-Saxon, Anglo-Norman, and Anglo-Latin periods. The second part of the book is devoted to a detailed study of the English language in the Middle Ages. It begins with a chapter on the Anglo-Saxon period, and then proceeds to the Anglo-Norman and Anglo-Latin periods. The third part of the book is devoted to a detailed study of the English language in the Modern period. It begins with a chapter on the Anglo-Norman period, and then proceeds to the Anglo-Latin period. The fourth part of the book is devoted to a detailed study of the English language in the Modern period. It begins with a chapter on the Anglo-Norman period, and then proceeds to the Anglo-Latin period.

The book is written in a clear and concise style, and is suitable for students of English literature and language. It is a valuable resource for anyone interested in the history of the English language.

alcohol/fuel ratio to a lower range than that needed to suppress detonation at higher compression ratios. The water curves increase in an approximately linear manner up to high flow rates where there is evidence of an upward trend, indicating an increased effectiveness in raising the allowable IMEP.

In all cases the injection of an additional weight of fluid allows the use of a higher IMEP, but the use of alcohol offers a vast advantage over water in that at the same fluid flow rate a much higher IMEP may be attained. This may be explained by the greater effectiveness of alcohol in altering the pressure-temperature-time combination leading to auto-ignition of the end gas, and this relation can be changed by altering the chemical composition of the unburned gases, or by a catalytic effect on the reaction, or more simply by evaporative cooling of the end gases. Alcohol has a lower viscosity than water and hence finer droplets are formed; in combination with this its higher rate of evaporation causes a more profound cooling effect upon the gases. In addition there is undoubtedly a greater chemical effect in the case of alcohol, which itself has a heating value and a rather high anti-knock rating. The injection of both fluids increases the number of mols of gas in the cylinder, and hence would tend to raise the pressure on the piston during the power stroke if the cooling effect were not sufficient to overcome this rise in pressure. In the region of low flow rates the great increase in IMEP is attributable to both evaporative cooling and to the combustion of part of the

alcohol; in this range the initial injection of the fluid occurs around 20-40°ATC, so that the adiabatic compression pressures in the cylinder are not lowered during most of the peak pressure region of the P-V diagram. At higher flow rates the initial angle of injection is advanced until at very high flows the injection is coincident with the spark, thus causing a profound cooling of the cylinder gases.

Figures 4, 5 and 6 represent lines of constant ISLC plotted on curves identical with 1, 2 and 3 for the range of fluid/fuel ratio from 0-1.0, which represents the only region that could possibly be considered as having any practical importance. The term liquid is here used to include both fuel plus anti-detonating fluid, and the curves indicate that for a given value of ISLC the injection of additional water results in a lower IMEP in all cases, thus giving positive evidence against its being practical. However, the positive slope of constant ISLC lines in the low region of alcohol/fuel ratio (below 0.4) indicates that for a given liquid consumption a higher detonation-free IMEP may be realized by injecting alcohol into the last part of the charge to burn, and hence its use is of considerable interest. At alcohol/fuel ratios above 0.4 the slope of the ISLC lines becomes negative, and the practicability of alcohol injection disappears in this upper region. The above statements refer in particular to compression ratios 6 and 7; at compression ratio 8 the slope becomes horizontal in the low range and little benefit is derived for cruising conditions.

Figure 7 represents a curve of detonation limited compression ratio vs. fluid/fuel ratio for the condition of constant IMEP=100 psia. This curve, as well as Figures 4, 5 and 6, is a cross-plot made from Figures 1, 2 and 3, and it indicates that in order to operate at a fixed IMEP more fluid must be injected at the higher compression ratios; this is to be expected, but it is interesting to note the vast superiority of alcohol over water for this purpose. Here the region of practical interest is that of higher F/A ratios, where the returns from injecting a small amount of alcohol are most pronounced.

Figure 8 shows a curve of indicated thermal efficiency vs. fluid/fuel ratio for 3 F/A ratios at compression ratio 7. The efficiencies are based on the heating value of the fuel alone, since the prime purpose of injecting the alcohol is as an anti-detonating agent rather than a fuel, and water, used for the same purpose, has no heating value. The water gives a slightly decreased thermal efficiency, whereas for alcohol/fuel ratios up to 0.7 the efficiency rises; the greatest increase is 3% at $F/A=.06$, and may be explained by the excess oxygen being available to burn the alcohol. As a primary combustion process this occurs too late in the power stroke to be highly efficient in itself, but it does, however, add a slight increment of pressure to raise the IMEP. In the case of water the decrease in thermal efficiency is caused by lowering the adiabatic compression pressure of the end gases in the cylinder.

THE HISTORY OF THE UNITED STATES OF AMERICA

The history of the United States of America is a story of a people who have built a great nation from a small colony. The story begins with the first settlers who came to the New World in search of a better life. They found a land of opportunity and freedom, and they built a nation that has become a model for the world. The story is one of courage, of sacrifice, and of the pursuit of the American dream. It is a story that has inspired generations and that will continue to inspire for many years to come.

THE FOUNDING OF THE NATION

The story of the United States begins with the first settlers who came to the New World in search of a better life. They found a land of opportunity and freedom, and they built a nation that has become a model for the world. The story is one of courage, of sacrifice, and of the pursuit of the American dream. It is a story that has inspired generations and that will continue to inspire for many years to come.

THE HISTORY OF THE UNITED STATES OF AMERICA

VII - CONCLUSIONS

As a result of this investigation the following conclusions are reached:

(1) At all F/A ratios and compression ratios the injection of ethyl alcohol is vastly superior to the use of water. In the useful range of fluid/fuel ratios (below 0.5) the injection of alcohol results in as much as a 40% increase in the detonation limited IMEP over that which could be obtained with no anti-detonating fluid. At the same fluid/fuel ratio in the case of water a 20% increase is obtained. As the fluid/fuel ratio increases these percentage gains increase, but at the expense of prohibitively high flow rate for extended operation.

(2) At a constant (and low) ISLC in the case of alcohol a higher IMEP may be obtained with using a low F/A ratio. However, with water injection and constant ISLC it is necessary to use a high F/A ratio to obtain the optimum detonation-free IMEP.

(3) At fluid/fuel ratios below 0.5 a slightly higher IMEP is obtainable by injecting a given weight of alcohol than by adding the same weight of fuel to the mixture, whereas low rates of water flow are not as effective as enrichening the mixture with additional fuel within the range of cruising F/A ratios herein investigated.

(4) The injection of alcohol is highly effective in raising the allowable compression ratio in order to take advantage of higher thermal efficiency.

CHAPTER IV

THE HISTORY OF THE UNITED STATES

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THE HISTORY OF THE UNITED STATES

The history of the United States is a story of growth and development. It begins with the first settlers who came to the continent in search of a new home. They found a land of vast resources and a people who were eager to learn from them. The story of the United States is a story of the struggle for freedom and the pursuit of happiness. It is a story of the triumph of the human spirit over adversity and the power of unity in the face of adversity. The story of the United States is a story of the growth of a nation from a small colony to a great power. It is a story of the development of a people from a simple folk to a sophisticated and cultured nation. The story of the United States is a story of the triumph of the human spirit over adversity and the power of unity in the face of adversity.

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THE HISTORY OF THE UNITED STATES

CHAPTER IV

(5) In order to operate at a given IMEP a lower octane fuel can be used in conjunction with direct cylinder injection of alcohol or water, with the former being more effective.

(6) The difficulties introduced by the installation, timing, and maintenance of an injection pump and nozzle, together with auxiliary supply, might easily overshadow the aforementioned advantages associated with direct cylinder injection. This would be especially true for a multi-cylinder installation.

(7) Some of the complications of a direct injection system could be obviated by using gasoline both as primary fuel and anti-detonating fluid (see appendix XII-a).

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- 3 - "Internal Combustion Engines" by Polson.
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CHAPTER - 100

Section 100 - 1. General

Section 100 - 2. General

Section 100 - 3. General

Section 100 - 4. General

Section 100 - 5. General

Section 100 - 6. General

Section 100 - 7. General

Section 100 - 8. General

Section 100 - 9. General

IX - NOMENCLATURE AND FORMULAESymbols:

Pa	-	Corrected barometric pressure (in. Hg.)
Ta	-	Atmospheric temperature ($^{\circ}$ R)
Pe	-	Exhaust pressure (in. H ₂ O)
Pi	-	Inlet pressure (in. Hg.)
Ti	-	Inlet temperature ($^{\circ}$ F)
Ma	-	Mass rate of air flow (lbs/sec)
Wf	-	Mass rate of fuel flow (lbs/sec)
Ww	-	Mass rate of water flow (lbs/sec)
Wa	-	Mass rate of alcohol flow (lbs/sec)
B.L.	-	Brake load (in Hg.)
BMEP	-	Brake mean effective pressure (psia)
FMEP	-	Friction mean effective pressure (psia)
IMEP	-	Indicated mean effective pressure (psia)
IHP	-	Indicated horsepower.
ISLC	-	Indicated specific liquid consumption (lbs.liq/IHP hr.)
F/A	-	Fuel/air ratio.
S.A.	-	Spark advance ($^{\circ}$ BTC)
h	-	Orifice differential pressure (in. H ₂ O)
Vd	-	Displacement volume (cu.in.)

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Formulae:

$$(a) \quad P_a = 30 + \frac{\text{mm HG} - 762}{25.4} - \frac{\text{mm HG} \times T^{\circ}\text{C} \times 6.4}{10^6}$$

$$(b) \quad M_a = .01825 \times \frac{P_a \times h}{T_a}^{1/2}$$

$$(c) \quad W_f = F/A \times M_a.$$

$$(d) \quad \text{BMEP} = 4.245 \times \text{B.L.}$$

$$(e) \quad \text{FMEP} = 4.245 \times \text{F.L.}$$

$$(f) \quad \text{IMEP} = \text{BMEP} + \text{FMEP}.$$

$$(g) \quad \text{IHP} = \frac{\text{IMEP} \times V_d \times \text{RPM}}{792,000} = .06125 \text{ IMEP}$$

$$(h) \quad \text{ISFC} = \frac{W_f \times 3600}{\text{IHP}}$$

$$(i) \quad \text{ISLC} = \frac{(W_f + W_w) \times 3600}{\text{IHP}}$$

$$(j) \quad i = \frac{2545}{\text{ISFC} \times 19,300}$$

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (1)$$

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (2)$$

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (3)$$

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (4)$$

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (5)$$

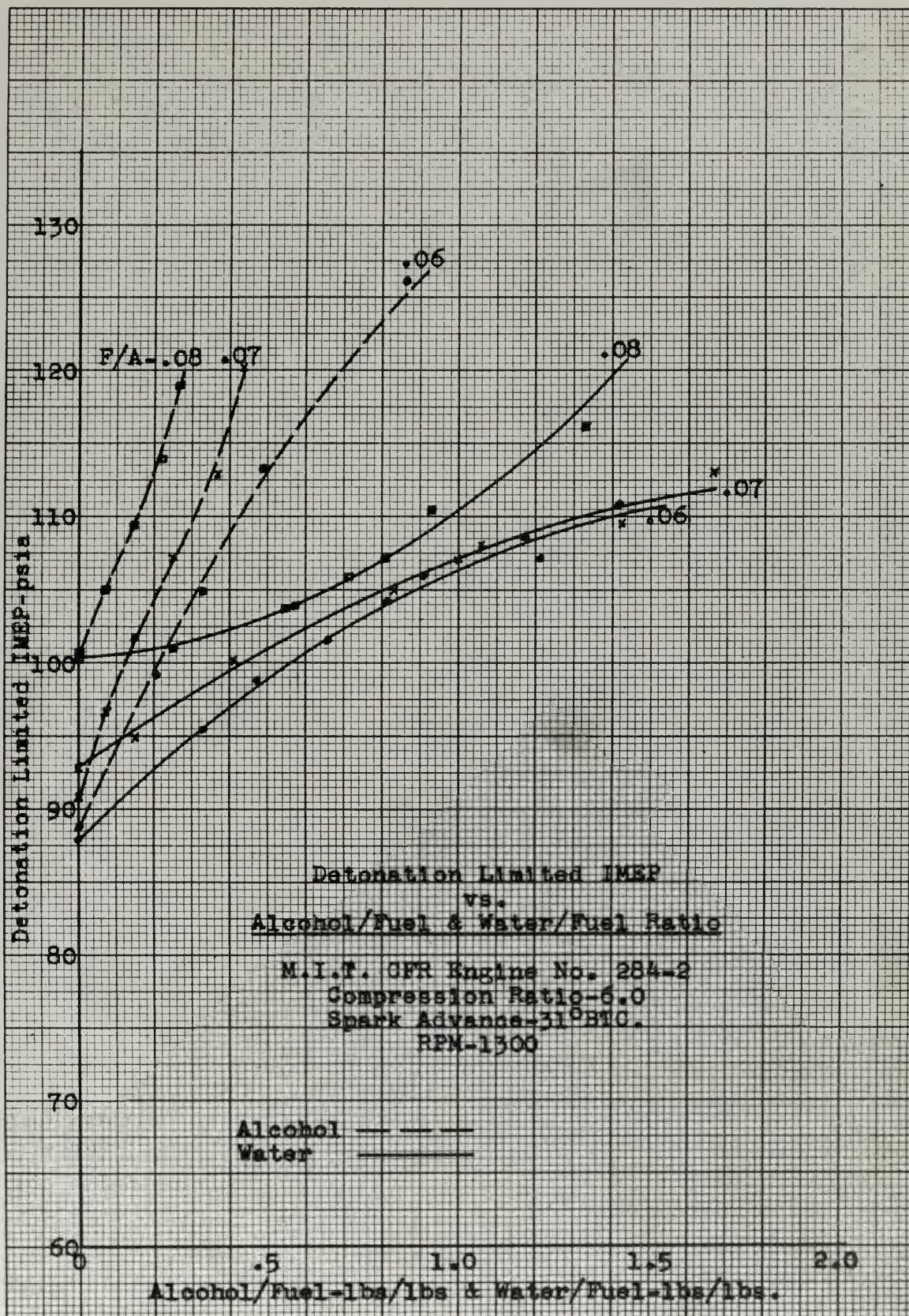
$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (6)$$

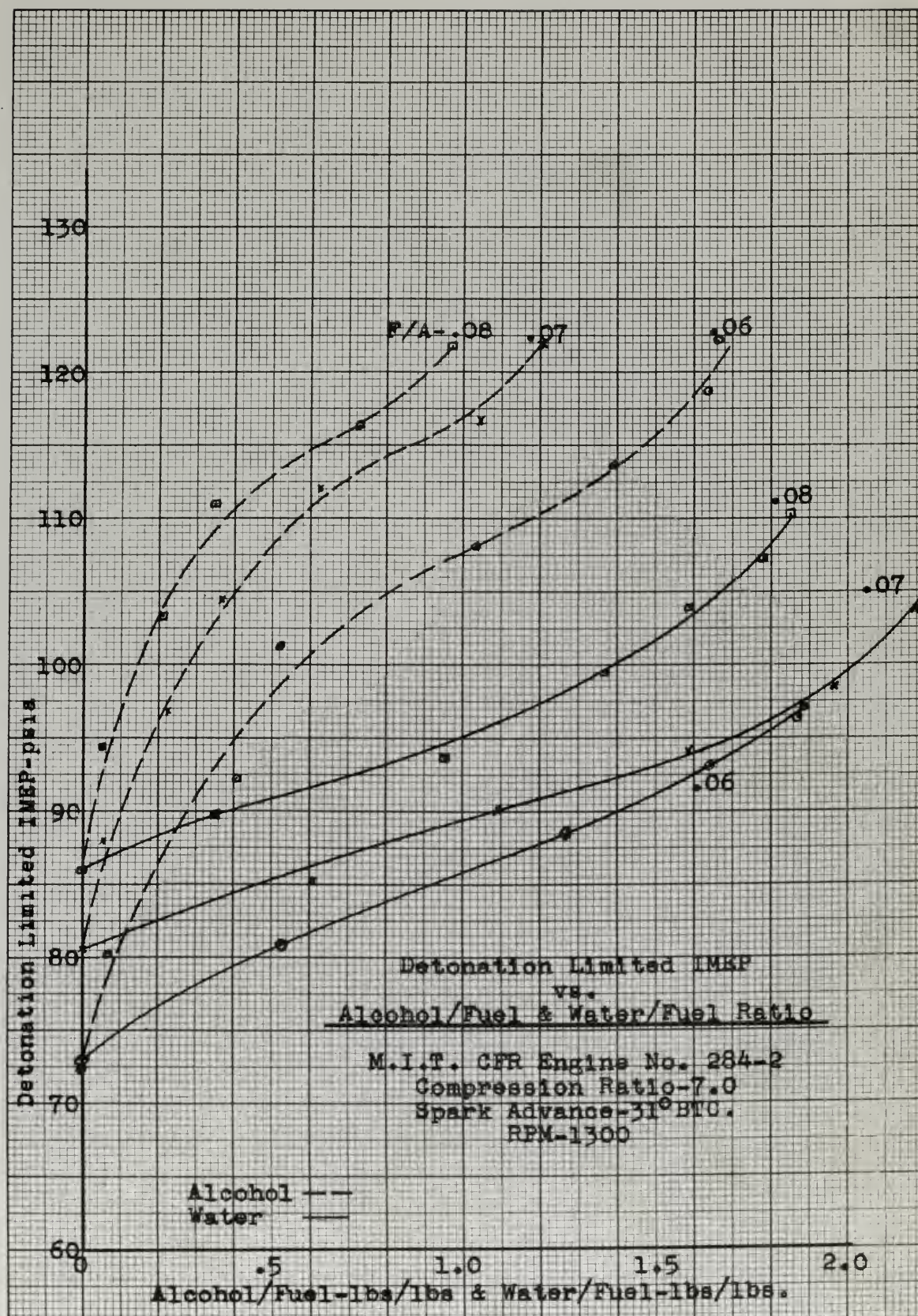
$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (7)$$

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (8)$$

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (9)$$

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2} \quad (10)$$





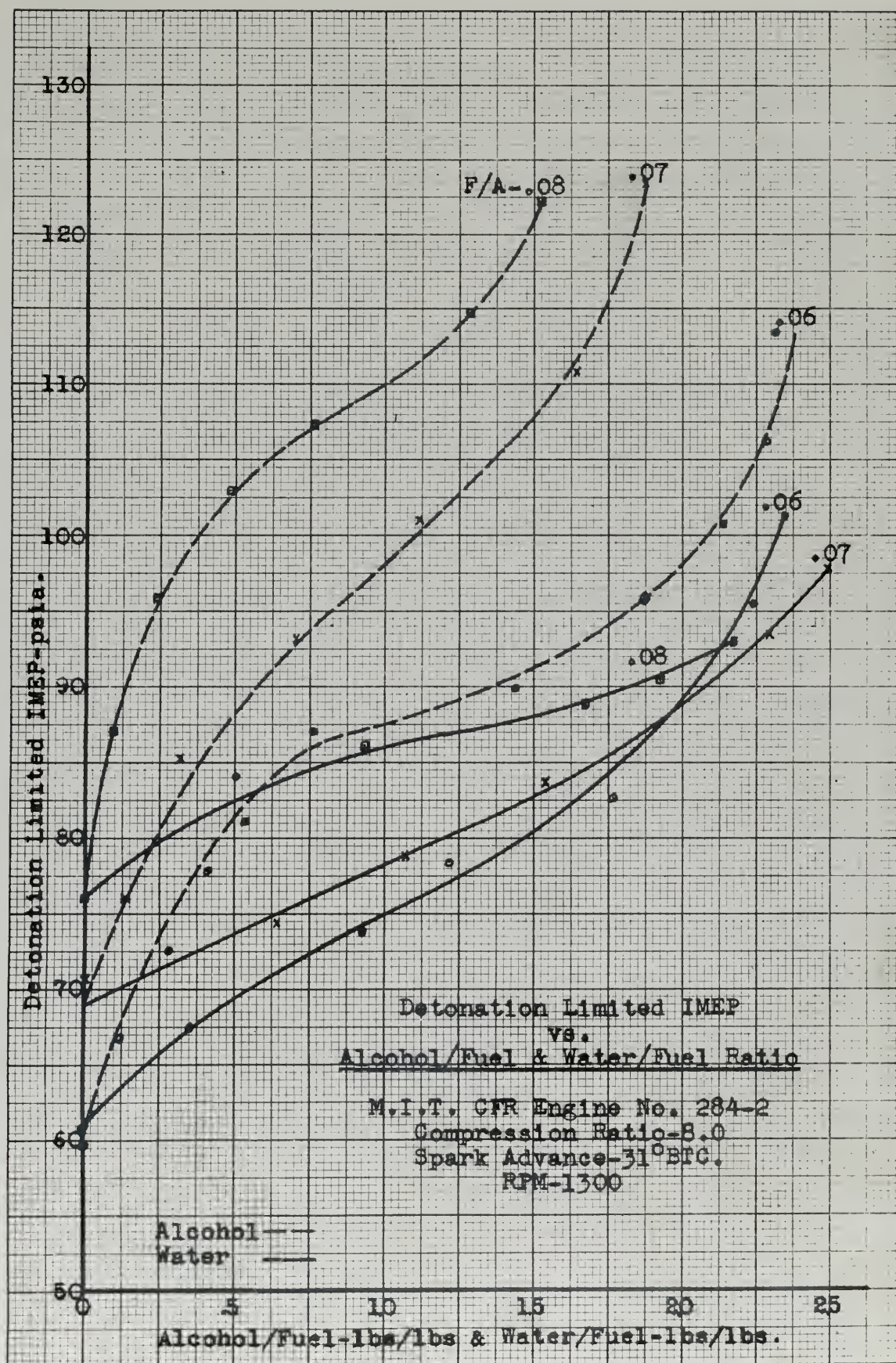


Fig. 3

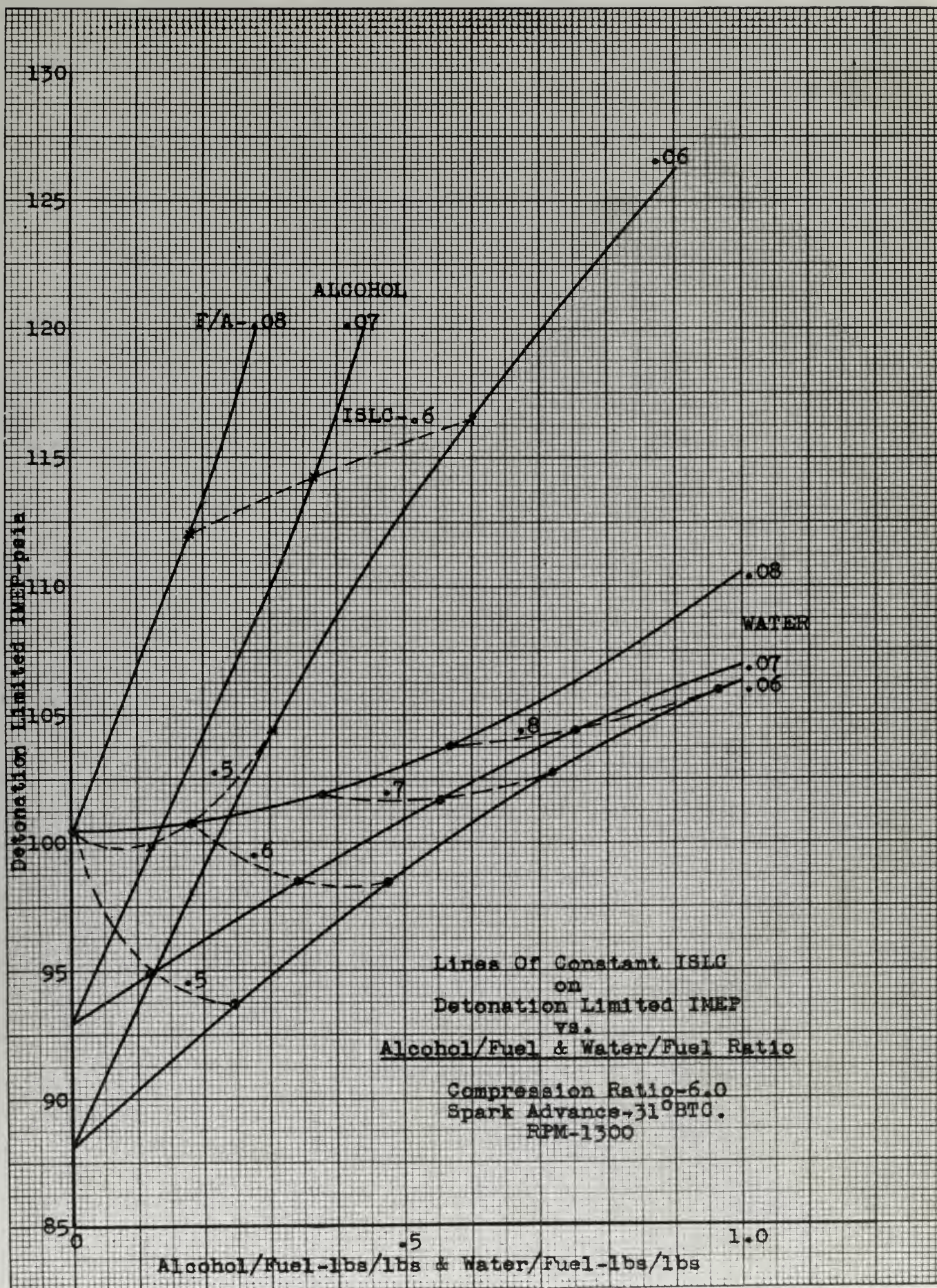


Fig. 4



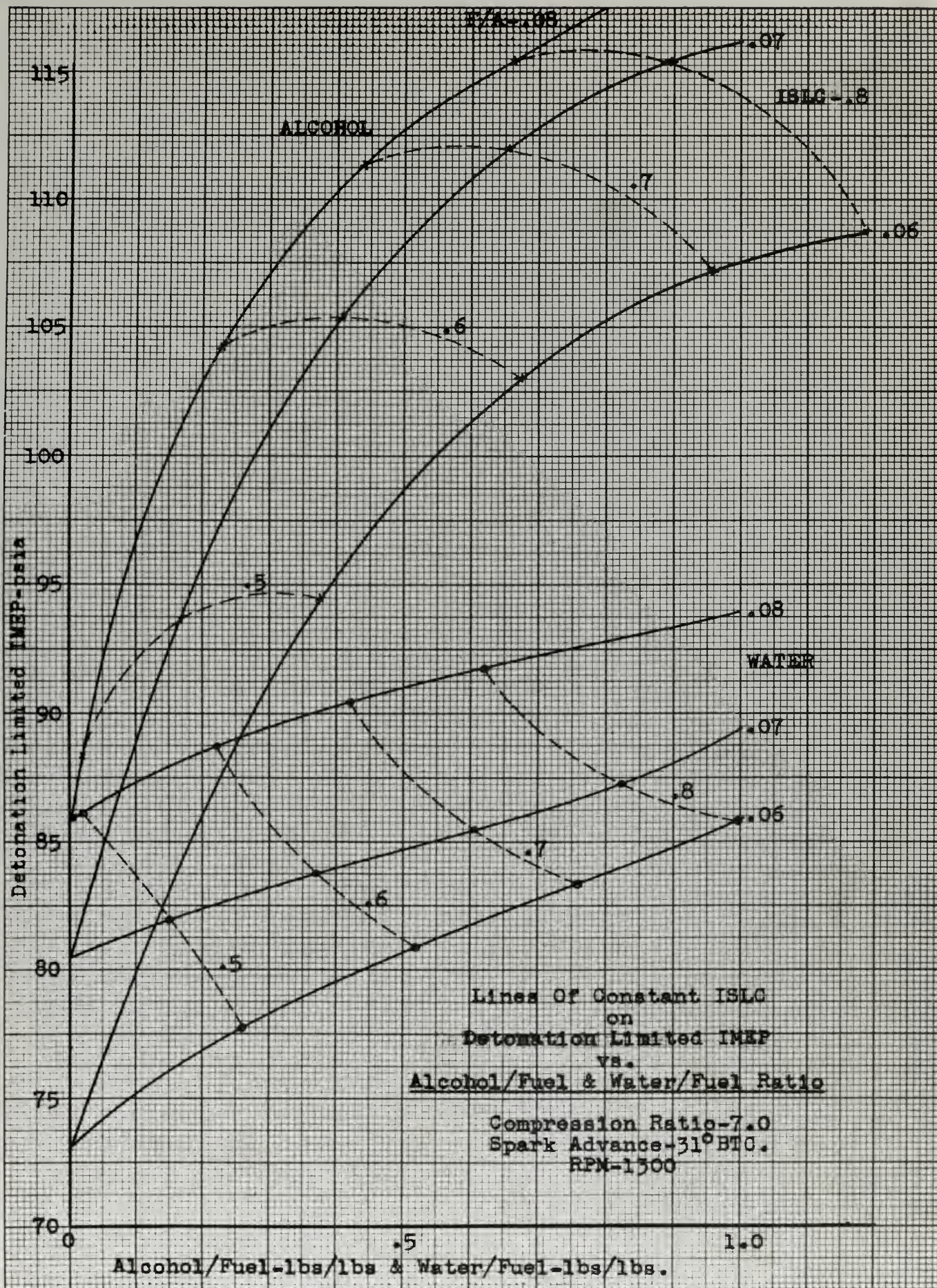


Fig. 5

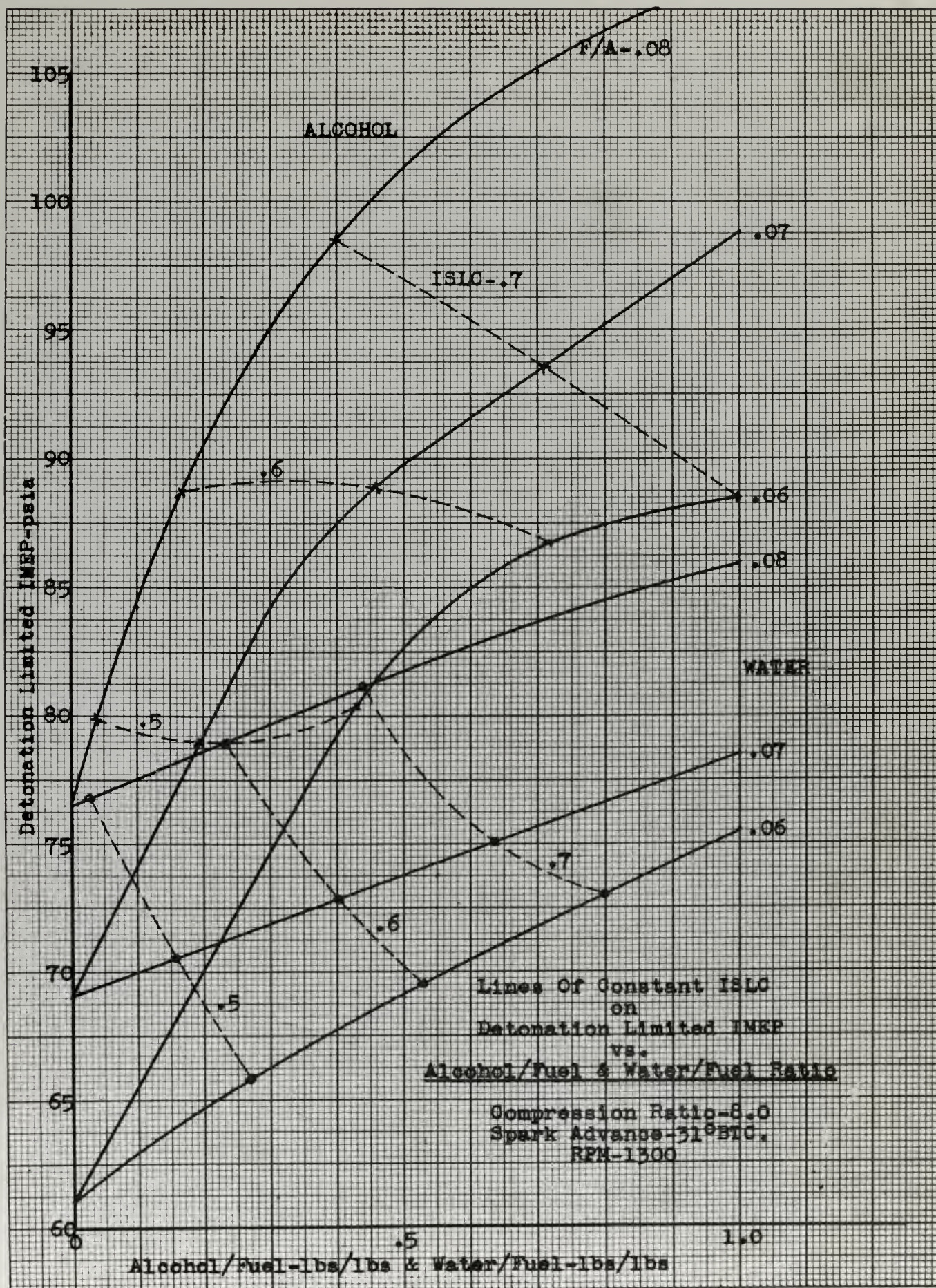


Fig. 6

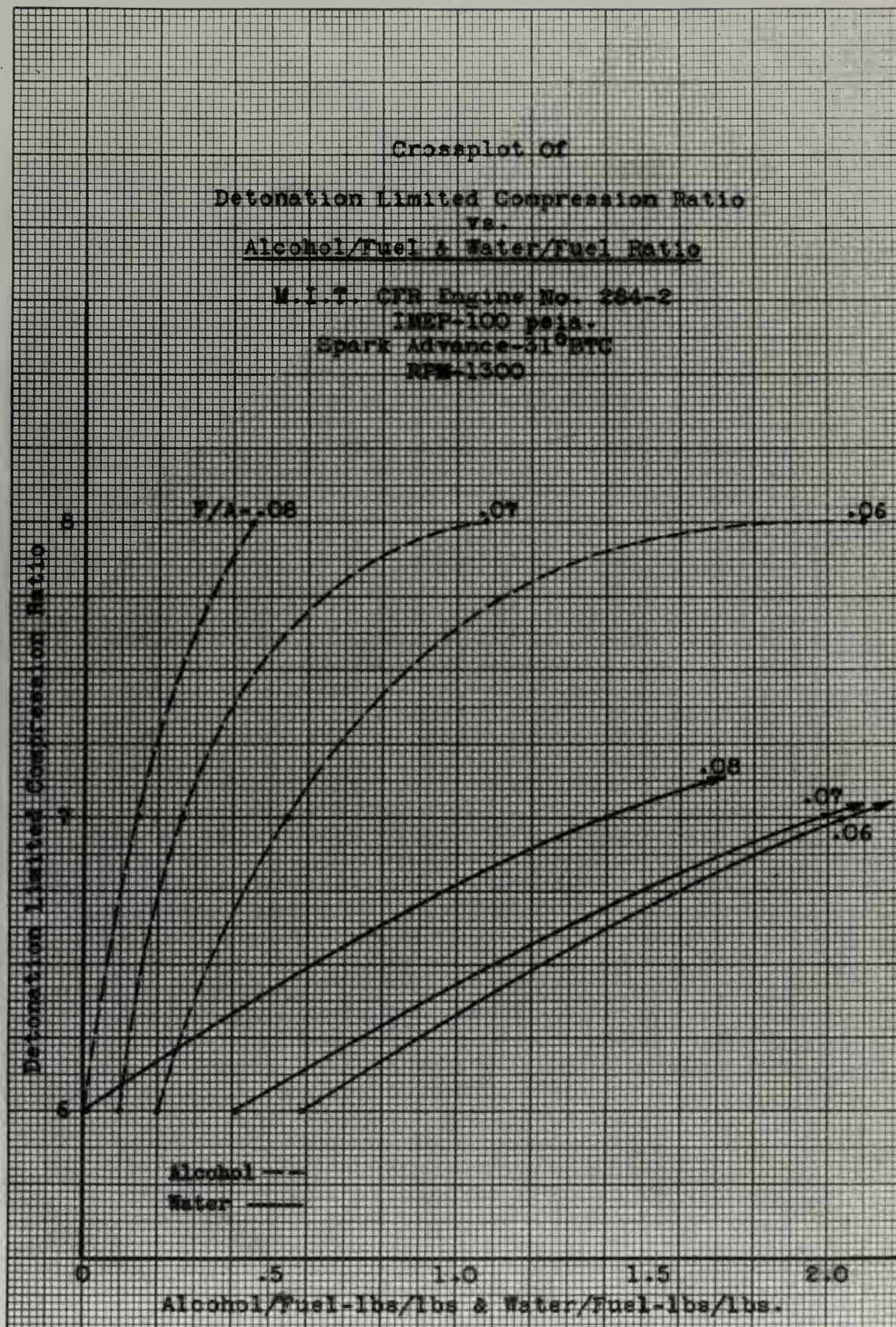
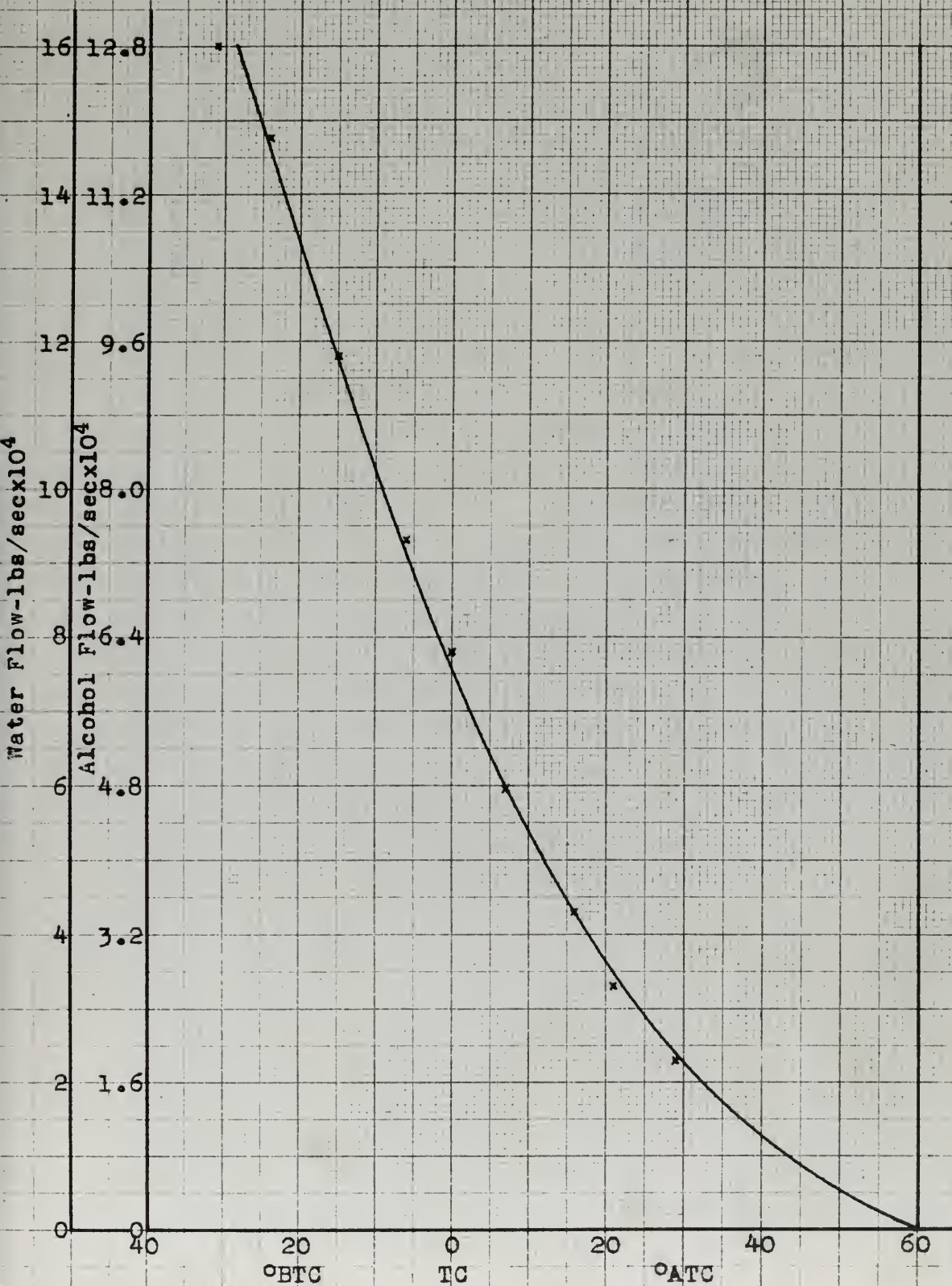


Fig. 7

Initial and Final Injection Angles
vs.
Fluid Flow Rate

American Bosch Single Piston Pump
APE 1B 70P 300 5 X221 58201



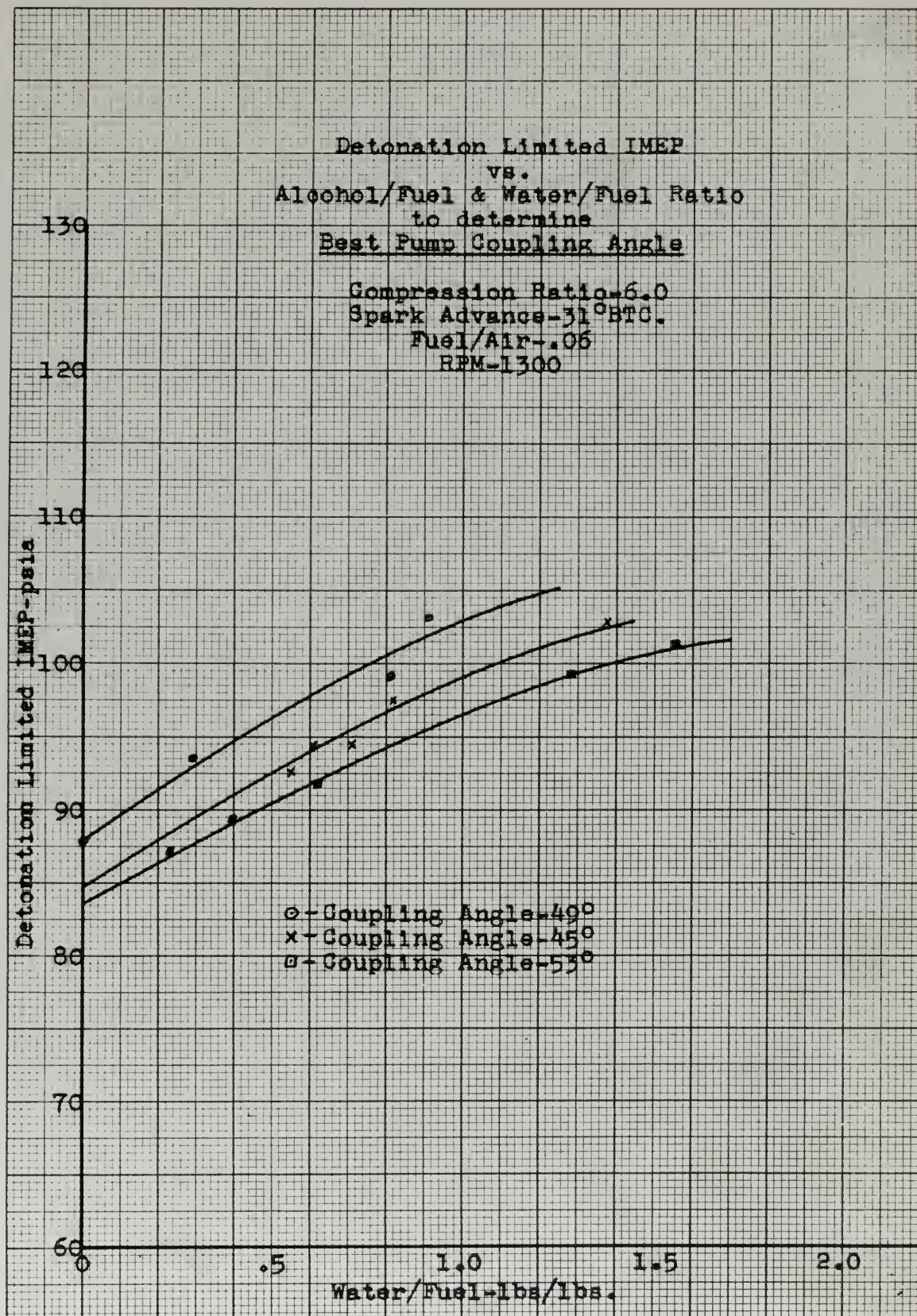


Fig. 10

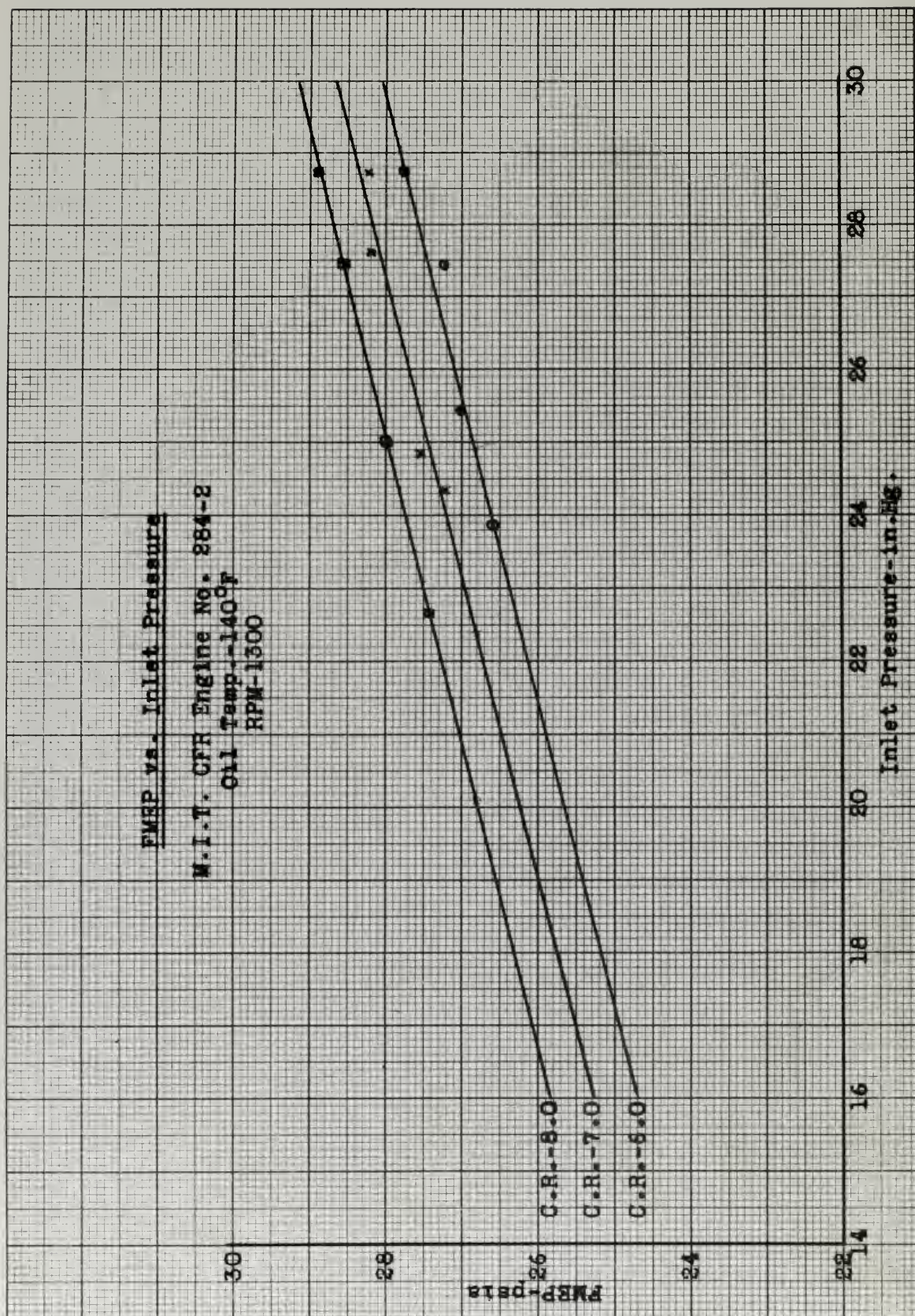


Fig. 11

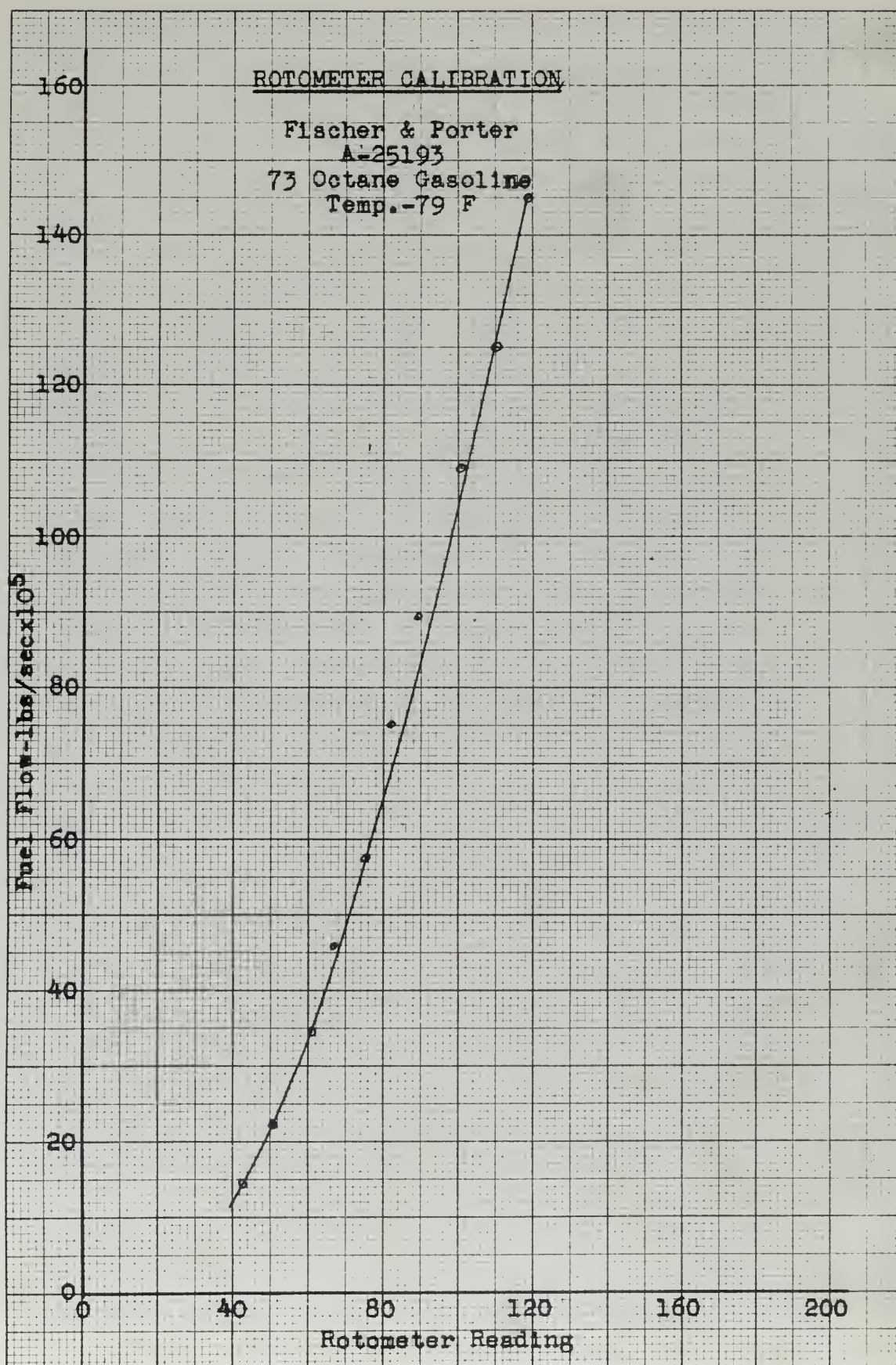


Fig. 12

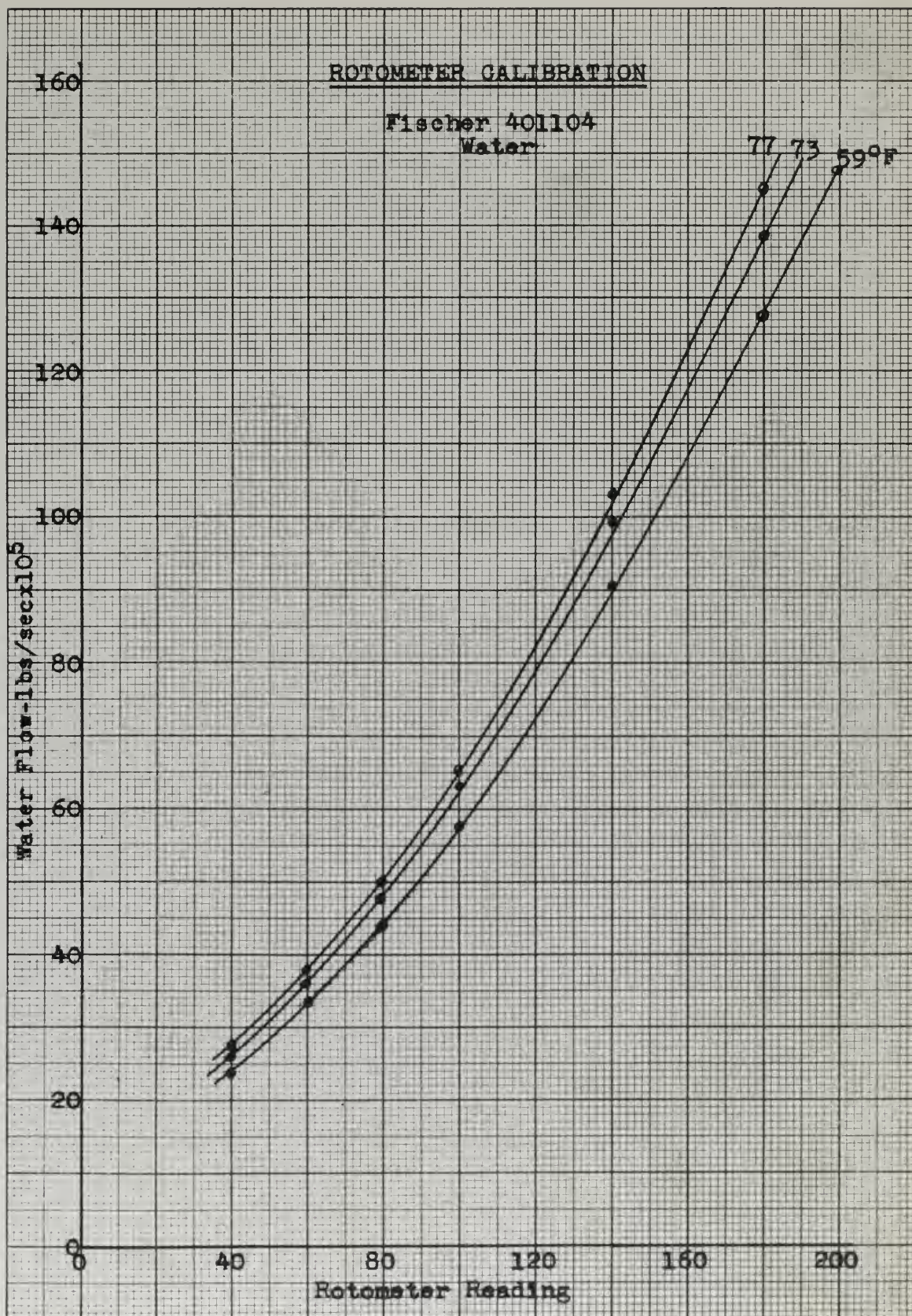


Fig. 13



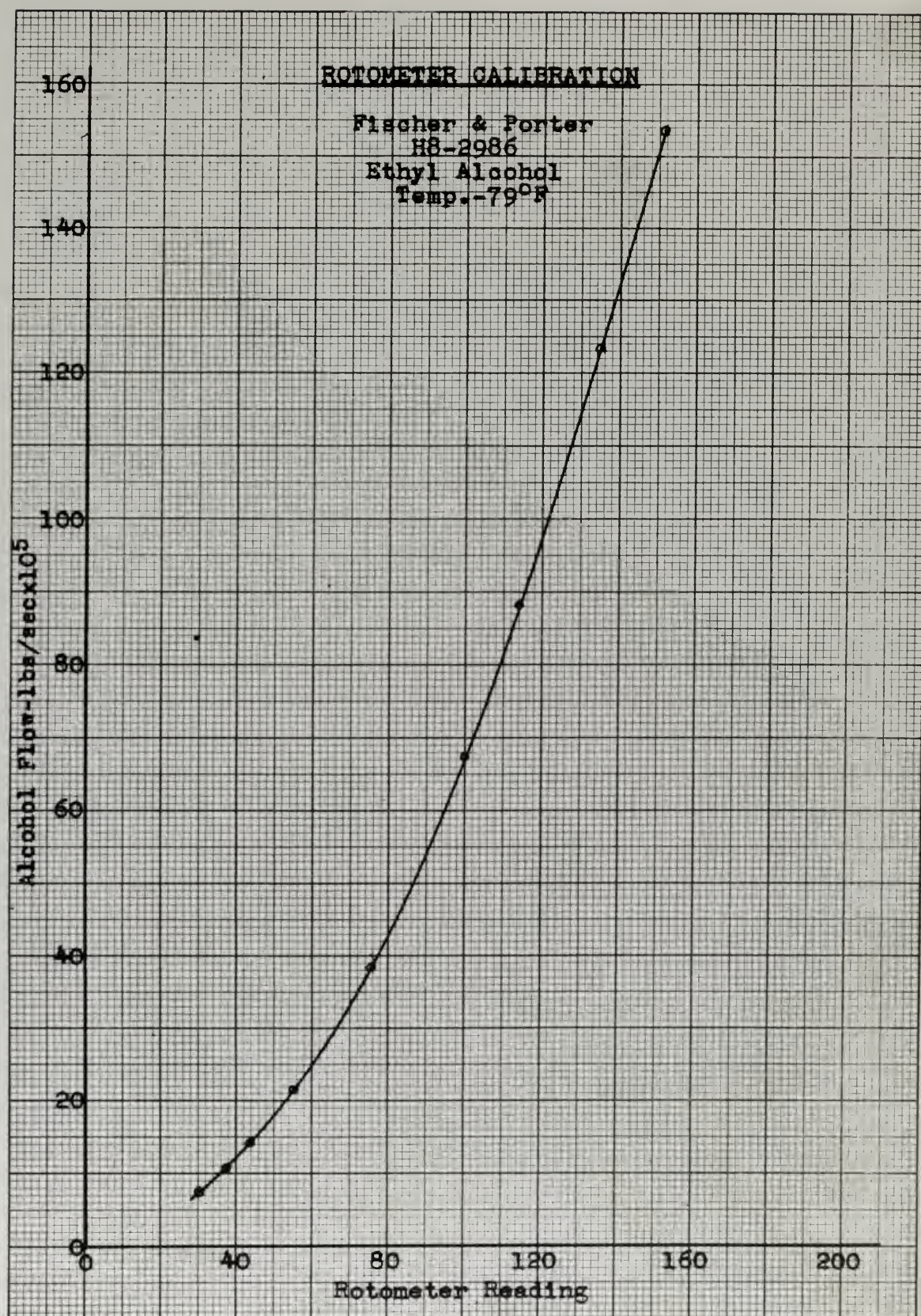


Fig. 14

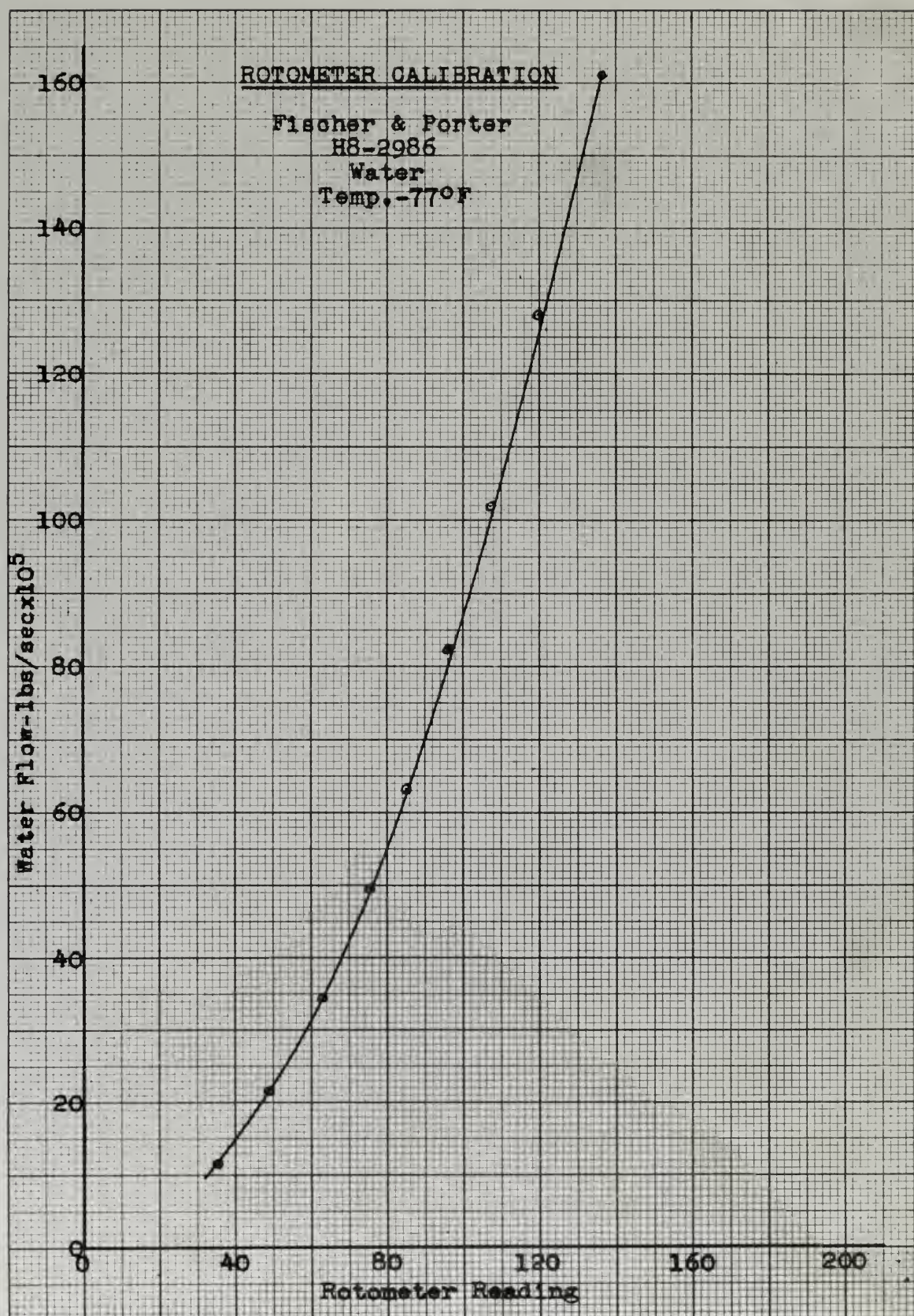
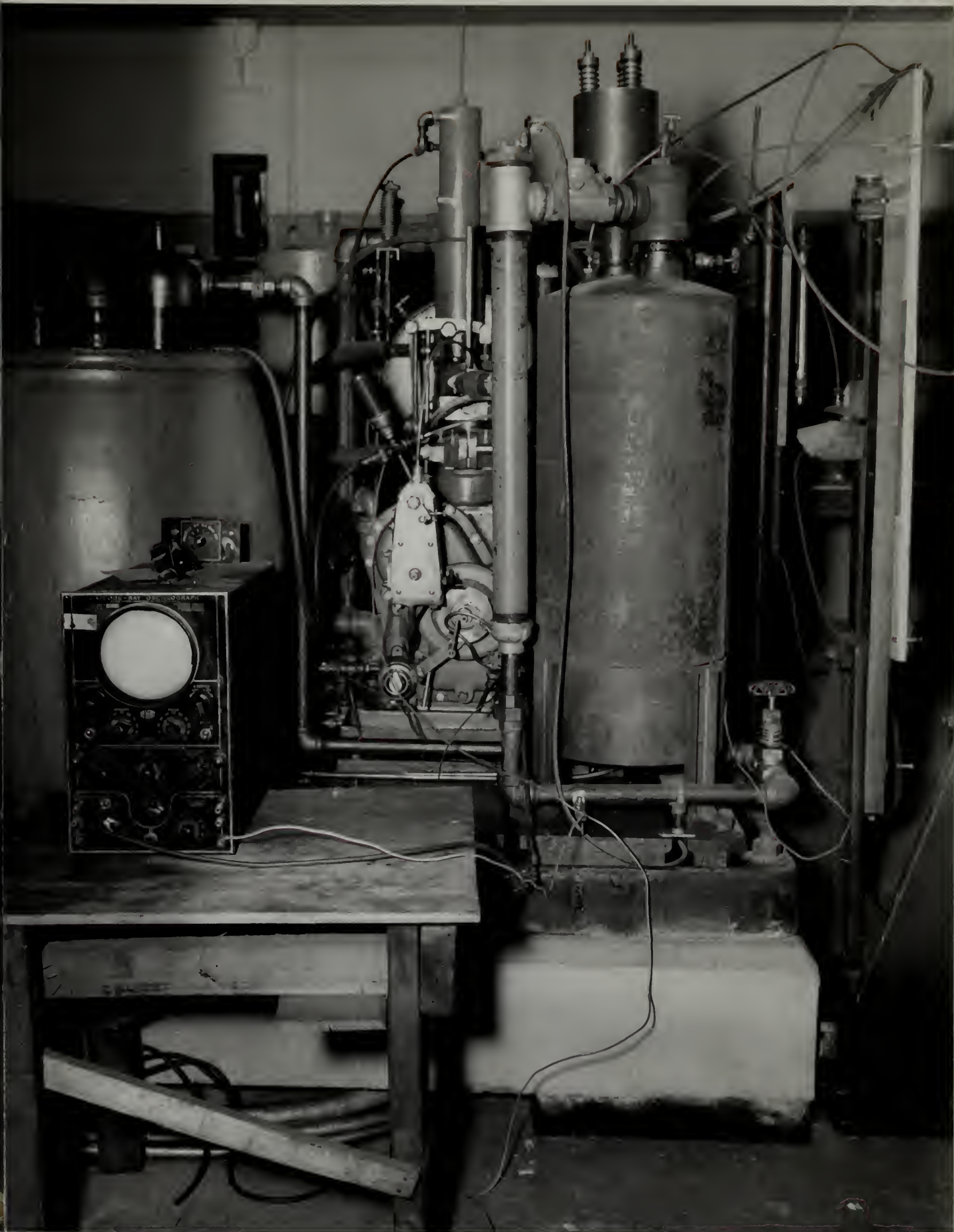


Fig. 15





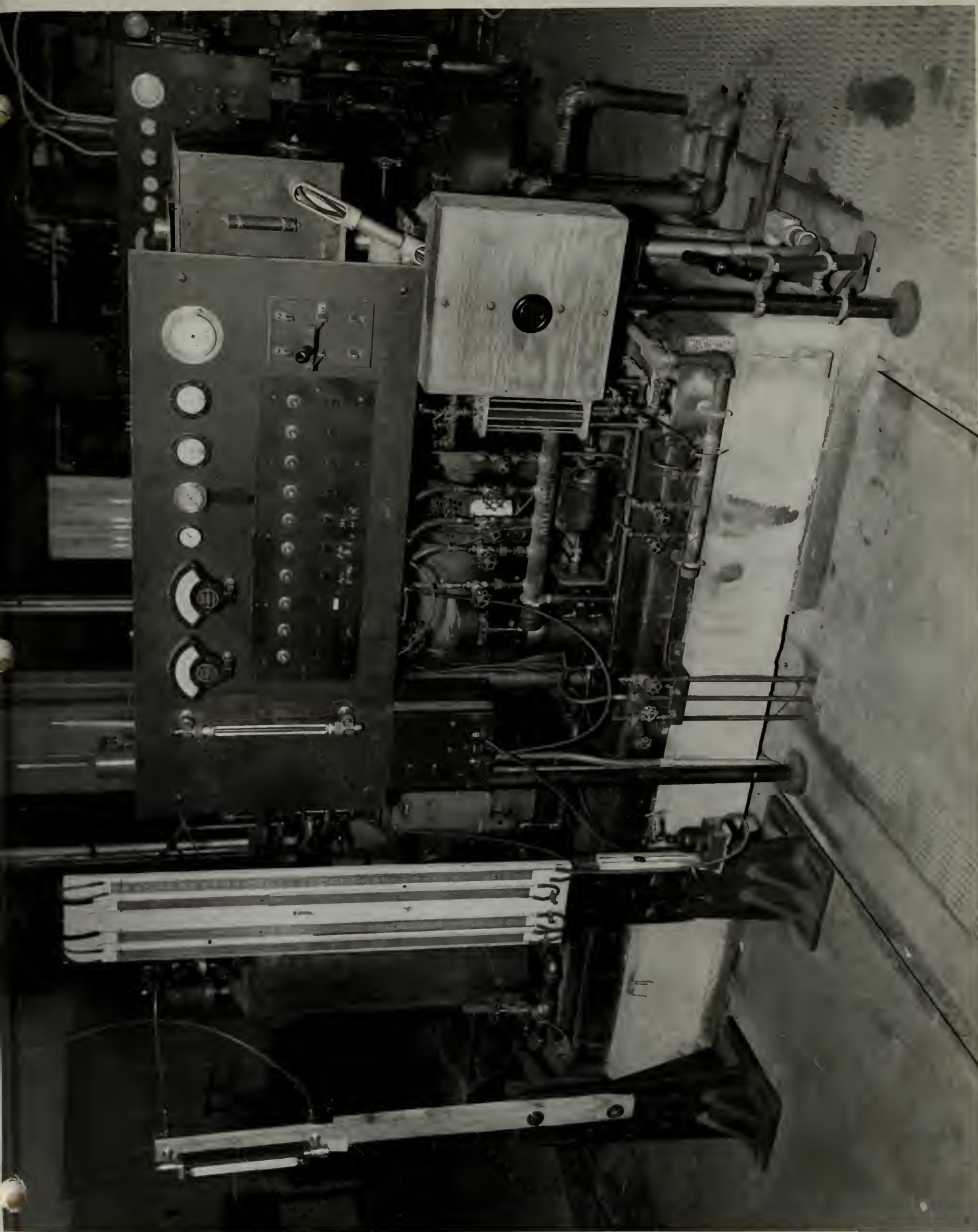


FIG. 17

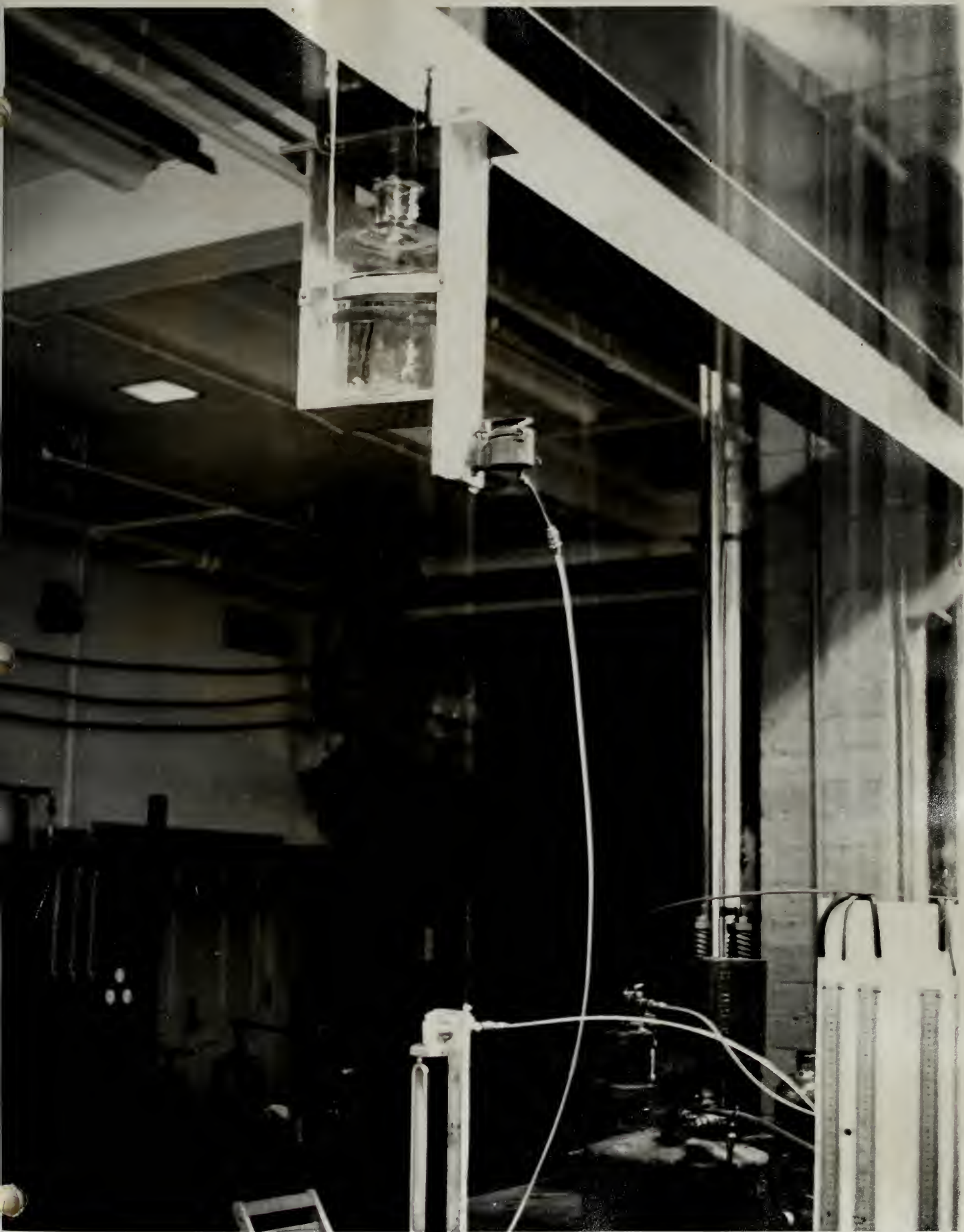


Fig. 18

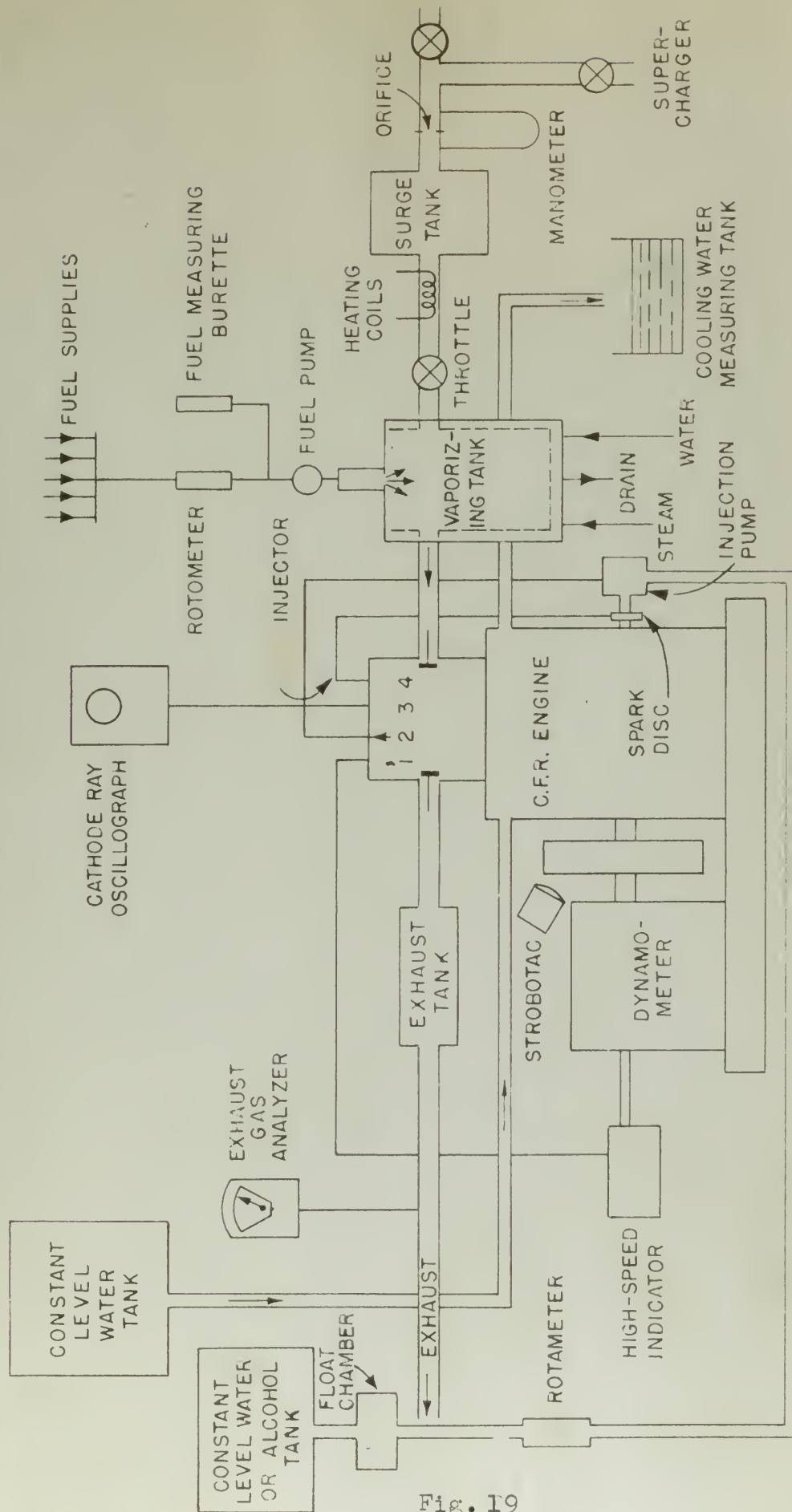


Fig. 19

1. INDICATOR PICKUP
2. WATER OR ALCOHOL INJECTION NOZZLE
3. RATE OF PRESSURE PICKUP
4. SPARK PLUG

C.F.R. ENGINE SETUP

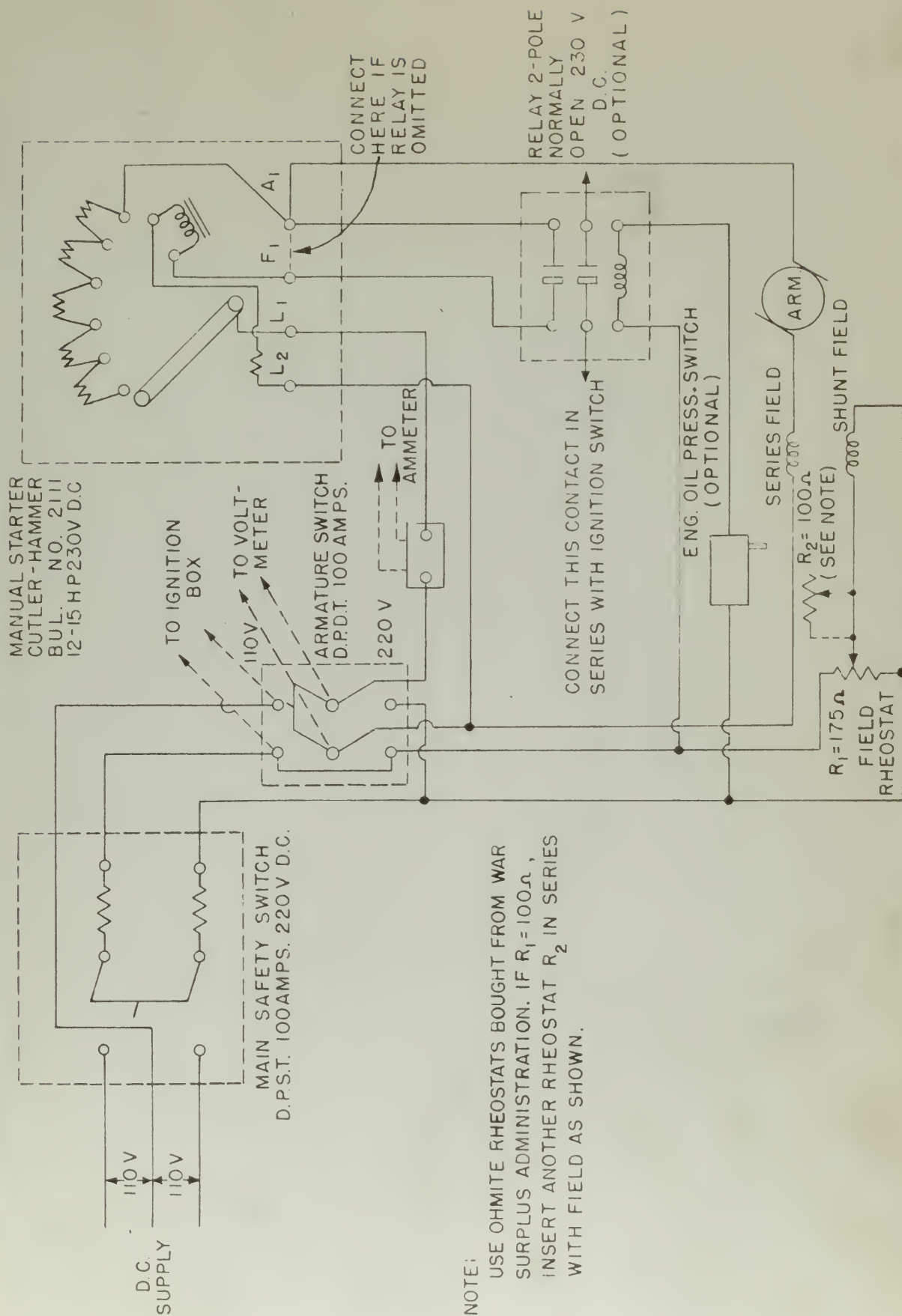
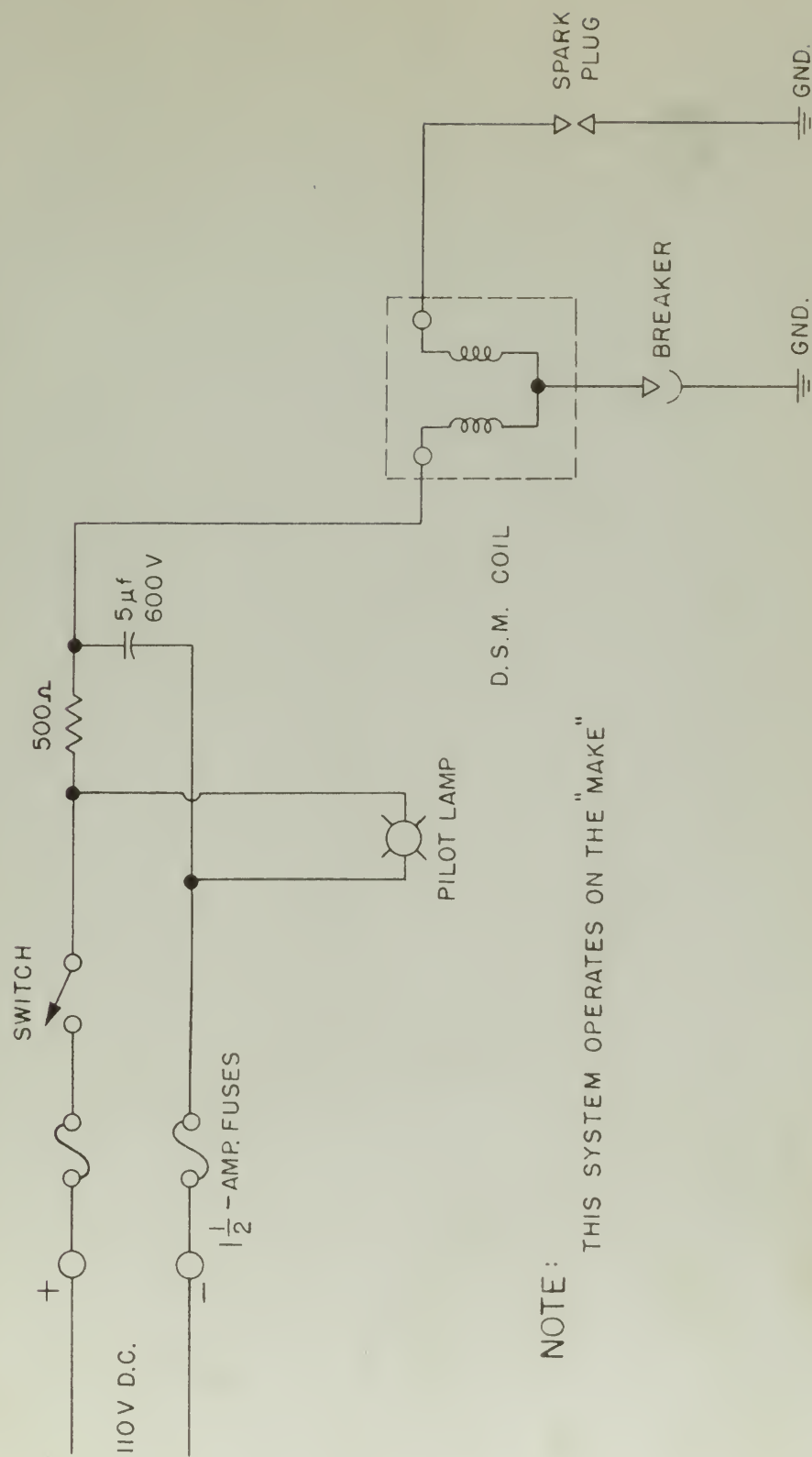
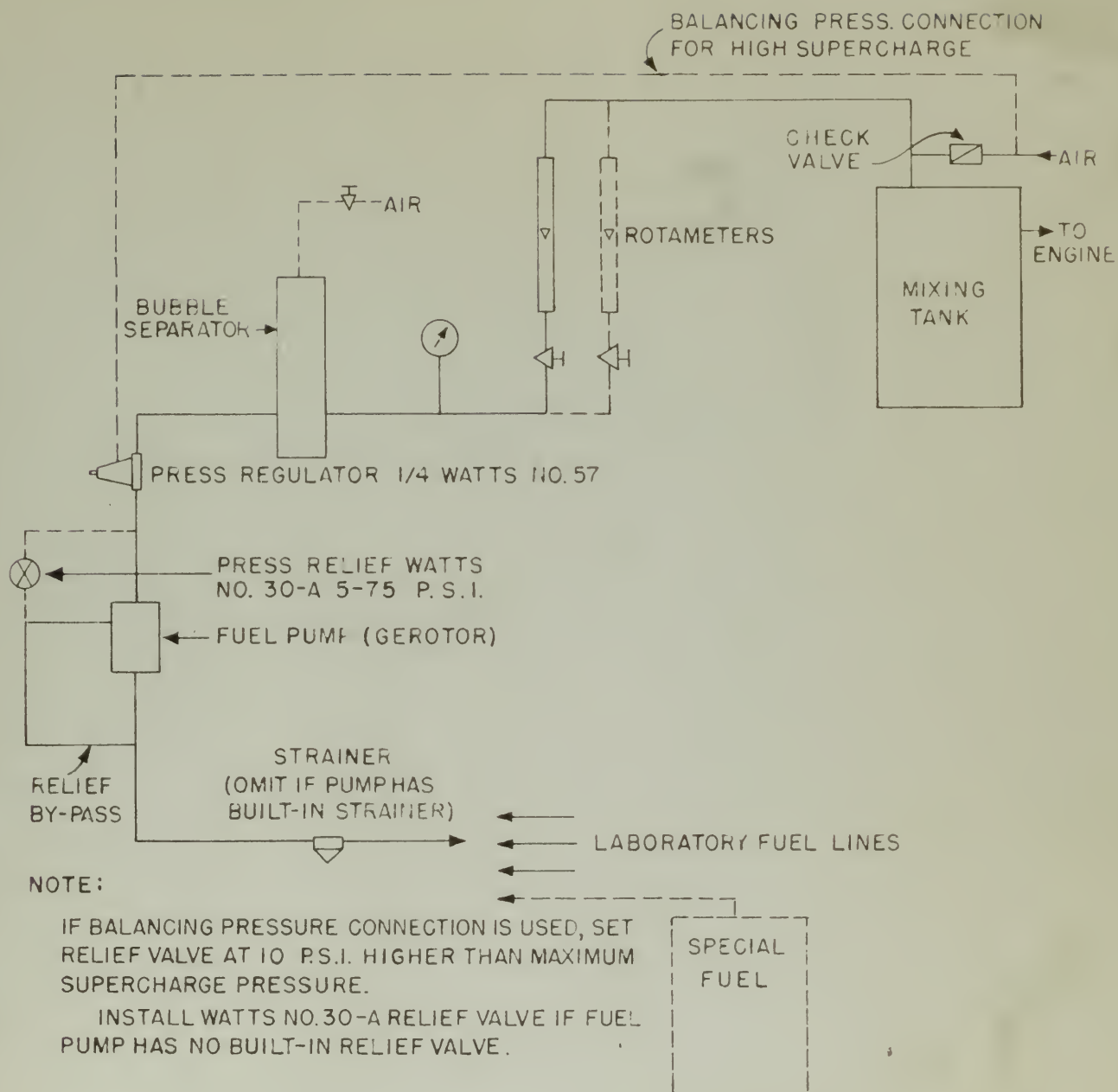


Fig. 20



NOTE: THIS SYSTEM OPERATES ON THE "MAKE"

WIRING DIAGRAM OF IGNITION SYSTEM



SCHEMATIC DIAGRAM OF FUEL SYSTEM

XI - EXPERIMENTAL DATA

Initial Angle of Injection vs. Mass Rate of Water Flow

Constant pump coupling angle - 49°

Constant RPM - 1300

Water temperature - 78°F

<u>Roto. Rdg.</u>	<u>Angle</u>	<u>lbs/secx10⁴</u>
200	31 BTC	16.0
183	24 BTC	14.75
154	15 BTC	11.8
130.5	6 BTC	9.3
114.5	0 TC	7.8
93	7 ATC	5.95
69	16 ATC	4.3
51.5	21 ATC	3.3
36	29 ATC	2.3

ROTOMETER CALIBRATION

Fischer & Porter
H8-2986

Alcohol
Temperature 79°F

<u>Roto. Rdg.</u>	<u>W gms</u>	<u>T sec</u>	<u>lbs/secx10⁵</u>
30	4	114.9	7.67
37.5	5	103.3	10.68
44	3	46.7	14.14
55.5	10	102.9	21.4
76	10	57.26	38.4
100	20	65.3	67.5
114	20	49.9	88.4
135	30	53.6	123.2
151	30	43.1	153.5
165	40	49.8	177.0
197	40	36.6	241.0

Water
Temperature 77°F

<u>Roto. Rdg.</u>	<u>W gms</u>	<u>T sec</u>	<u>lbs/secx10⁵</u>
35.5	10	185.1	11.92
49	5	51.9	21.25
63	10	64.2	34.3
75	10	44.6	49.5
85	15	52.4	63.0
96	20	53.3	82.8
107	25	54.1	102.0
120	20	34.3	128.7
135.5	40	54.8	161.0
150.5	30	33.7	196.3

ROTOMETER CALIBRATION

Fischer & Porter
A-25193

Gasoline 73 Octane
Temperature 78°F

<u>Roto. Rdg.</u>	<u>W gms</u>	<u>T sec</u>	<u>lbs/secx10³</u>
43	10	152.5	.145
50.5	10	99.3	.222
61.0	10	63.7	.346
67	30	144.5	.458
75	10	38.4	.575
82	30	88.3	.75
89.5	20	49.6	.889
101	20	40.5	1.09
111	30	53.0	1.25
119	40	61.9	1.425
128	20	28.5	1.55
135	50	64.7	1.70
145	50	59.6	1.85
176	50	37.2	2.96
198	50	30.6	3.60

EXPERIMENT NO. _____ TITLE *Determination of Best Pump Coupling Angle* _____ DATE 4/3/47 SLOAN LABORATORY
ENGINE _____ FUEL 73 Octane S.G. .719 WET BULB _____ DRY BULB 77°F
BORE 3.25" STROKE 4.50" COMPRESSION RATIO 6.0 BAROMETER (ACT.) 762.6 mm Hg (CORR.) 30.126 " Hg
CONSTANTS
BMFP = B.L. X 4245 RHP = B.L. X RPM

[illegible]

EXPERIMENT NO. _____ TITLE Alcohol Injection DATE 4/16/47 SLOAN LABORATORY
ENGINE CFR-9B FUEL Is Octane S.G. .719 WET BULB _____ DRY BULB 76°F
BORE 3.25" STROKE 4.50" COMPRESSION RATIO 6.0 BAROMETER (ACT.) 26.74 mm Hg. (CORR.) 30.103 "Hg

BHP = B.L. x RPM

BMEP = B.L. x

CONSTANTS

REMARKS	TIME RUN	RPM	B.L.	F.L.	TEMP. OIL JACQUES	P _i	P _e	T _i	AIR CONS.	FUEL CONS.	F ₁	S.A.	FUEL CORR.	Air. Cons. W ₁	Air. Cons. W ₂	W ₃	W ₄	W ₅	W ₆	W ₇	W ₈	W ₉	W ₁₀	W ₁₁	W ₁₂	W ₁₃	W ₁₄	W ₁₅	W ₁₆	W ₁₇	W ₁₈	W ₁₉	W ₂₀	W ₂₁	W ₂₂	W ₂₃	W ₂₄	W ₂₅	W ₂₆	W ₂₇	W ₂₈	W ₂₉	W ₃₀	W ₃₁	W ₃₂	W ₃₃	W ₃₄	W ₃₅	W ₃₆	W ₃₇	W ₃₈	W ₃₉	W ₄₀	W ₄₁	W ₄₂	W ₄₃	W ₄₄	W ₄₅	W ₄₆	W ₄₇	W ₄₈	W ₄₉	W ₅₀	W ₅₁	W ₅₂	W ₅₃	W ₅₄	W ₅₅	W ₅₆	W ₅₇	W ₅₈	W ₅₉	W ₆₀	W ₆₁	W ₆₂	W ₆₃	W ₆₄	W ₆₅	W ₆₆	W ₆₇	W ₆₈	W ₆₉	W ₇₀	W ₇₁	W ₇₂	W ₇₃	W ₇₄	W ₇₅	W ₇₆	W ₇₇	W ₇₈	W ₇₉	W ₈₀	W ₈₁	W ₈₂	W ₈₃	W ₈₄	W ₈₅	W ₈₆	W ₈₇	W ₈₈	W ₈₉	W ₉₀	W ₉₁	W ₉₂	W ₉₃	W ₉₄	W ₉₅	W ₉₆	W ₉₇	W ₉₈	W ₉₉	W ₁₀₀	W ₁₀₁	W ₁₀₂	W ₁₀₃	W ₁₀₄	W ₁₀₅	W ₁₀₆	W ₁₀₇	W ₁₀₈	W ₁₀₉	W ₁₁₀	W ₁₁₁	W ₁₁₂	W ₁₁₃	W ₁₁₄	W ₁₁₅	W ₁₁₆	W ₁₁₇	W ₁₁₈	W ₁₁₉	W ₁₂₀	W ₁₂₁	W ₁₂₂	W ₁₂₃	W ₁₂₄	W ₁₂₅	W ₁₂₆	W ₁₂₇	W ₁₂₈	W ₁₂₉	W ₁₃₀	W ₁₃₁	W ₁₃₂	W ₁₃₃	W ₁₃₄	W ₁₃₅	W ₁₃₆	W ₁₃₇	W ₁₃₈	W ₁₃₉	W ₁₄₀	W ₁₄₁	W ₁₄₂	W ₁₄₃	W ₁₄₄	W ₁₄₅	W ₁₄₆	W ₁₄₇	W ₁₄₈	W ₁₄₉	W ₁₅₀	W ₁₅₁	W ₁₅₂	W ₁₅₃	W ₁₅₄	W ₁₅₅	W ₁₅₆	W ₁₅₇	W ₁₅₈	W ₁₅₉	W ₁₆₀	W ₁₆₁	W ₁₆₂	W ₁₆₃	W ₁₆₄	W ₁₆₅	W ₁₆₆	W ₁₆₇	W ₁₆₈	W ₁₆₉	W ₁₇₀	W ₁₇₁	W ₁₇₂	W ₁₇₃	W ₁₇₄	W ₁₇₅	W ₁₇₆	W ₁₇₇	W ₁₇₈	W ₁₇₉	W ₁₈₀	W ₁₈₁	W ₁₈₂	W ₁₈₃	W ₁₈₄	W ₁₈₅	W ₁₈₆	W ₁₈₇	W ₁₈₈	W ₁₈₉	W ₁₉₀	W ₁₉₁	W ₁₉₂	W ₁₉₃	W ₁₉₄	W ₁₉₅	W ₁₉₆	W ₁₉₇	W ₁₉₈	W ₁₉₉	W ₂₀₀	W ₂₀₁	W ₂₀₂	W ₂₀₃	W ₂₀₄	W ₂₀₅	W ₂₀₆	W ₂₀₇	W ₂₀₈	W ₂₀₉	W ₂₁₀	W ₂₁₁	W ₂₁₂	W ₂₁₃	W ₂₁₄	W ₂₁₅	W ₂₁₆	W ₂₁₇	W ₂₁₈	W ₂₁₉	W ₂₂₀	W ₂₂₁	W ₂₂₂	W ₂₂₃	W ₂₂₄	W ₂₂₅	W ₂₂₆	W ₂₂₇	W ₂₂₈	W ₂₂₉	W ₂₃₀	W ₂₃₁	W ₂₃₂	W ₂₃₃	W ₂₃₄	W ₂₃₅	W ₂₃₆	W ₂₃₇	W ₂₃₈	W ₂₃₉	W ₂₄₀	W ₂₄₁	W ₂₄₂	W ₂₄₃	W ₂₄₄	W ₂₄₅	W ₂₄₆	W ₂₄₇	W ₂₄₈	W ₂₄₉	W ₂₅₀	W ₂₅₁	W ₂₅₂	W ₂₅₃	W ₂₅₄	W ₂₅₅	W ₂₅₆	W ₂₅₇	W ₂₅₈	W ₂₅₉	W ₂₆₀	W ₂₆₁	W ₂₆₂	W ₂₆₃	W ₂₆₄	W ₂₆₅	W ₂₆₆	W ₂₆₇	W ₂₆₈	W ₂₆₉	W ₂₇₀	W ₂₇₁	W ₂₇₂	W ₂₇₃	W ₂₇₄	W ₂₇₅	W ₂₇₆	W ₂₇₇	W ₂₇₈	W ₂₇₉	W ₂₈₀	W ₂₈₁	W ₂₈₂	W ₂₈₃	W ₂₈₄	W ₂₈₅	W ₂₈₆	W ₂₈₇	W ₂₈₈	W ₂₈₉	W ₂₉₀	W ₂₉₁	W ₂₉₂	W ₂₉₃	W ₂₉₄	W ₂₉₅	W ₂₉₆	W ₂₉₇	W ₂₉₈	W ₂₉₉	W ₃₀₀	W ₃₀₁	W ₃₀₂	W ₃₀₃	W ₃₀₄	W ₃₀₅	W ₃₀₆	W ₃₀₇	W ₃₀₈	W ₃₀₉	W ₃₁₀	W ₃₁₁	W ₃₁₂	W ₃₁₃	W ₃₁₄	W ₃₁₅	W ₃₁₆	W ₃₁₇	W ₃₁₈	W ₃₁₉	W ₃₂₀	W ₃₂₁	W ₃₂₂	W ₃₂₃	W ₃₂₄	W ₃₂₅	W ₃₂₆	W ₃₂₇	W ₃₂₈	W ₃₂₉	W ₃₃₀	W ₃₃₁	W ₃₃₂	W ₃₃₃	W ₃₃₄	W ₃₃₅	W ₃₃₆	W ₃₃₇	W ₃₃₈	W ₃₃₉	W ₃₄₀	W ₃₄₁	W ₃₄₂	W ₃₄₃	W ₃₄₄	W ₃₄₅	W ₃₄₆	W ₃₄₇	W ₃₄₈	W ₃₄₉	W ₃₅₀	W ₃₅₁	W ₃₅₂	W ₃₅₃	W ₃₅₄	W ₃₅₅	W ₃₅₆	W ₃₅₇	W ₃₅₈	W ₃₅₉	W ₃₆₀	W ₃₆₁	W ₃₆₂	W ₃₆₃	W ₃₆₄	W ₃₆₅	W ₃₆₆	W ₃₆₇	W ₃₆₈	W ₃₆₉	W ₃₇₀	W ₃₇₁	W ₃₇₂	W ₃₇₃	W ₃₇₄	W ₃₇₅	W ₃₇₆	W ₃₇₇	W ₃₇₈	W ₃₇₉	W ₃₈₀	W ₃₈₁	W ₃₈₂	W ₃₈₃	W ₃₈₄	W ₃₈₅	W ₃₈₆	W ₃₈₇	W ₃₈₈	W ₃₈₉	W ₃₉₀	W ₃₉₁	W ₃₉₂	W ₃₉₃	W ₃₉₄	W ₃₉₅	W ₃₉₆	W ₃₉₇	W ₃₉₈	W ₃₉₉	W ₄₀₀	W ₄₀₁	W ₄₀₂	W ₄₀₃	W ₄₀₄	W ₄₀₅	W ₄₀₆	W ₄₀₇	W ₄₀₈	W ₄₀₉	W ₄₁₀	W ₄₁₁	W ₄₁₂	W ₄₁₃	W ₄₁₄	W ₄₁₅	W ₄₁₆	W ₄₁₇	W ₄₁₈	W ₄₁₉	W ₄₂₀	W ₄₂₁	W ₄₂₂	W ₄₂₃	W ₄₂₄	W ₄₂₅	W ₄₂₆	W ₄₂₇	W ₄₂₈	W ₄₂₉	W ₄₃₀	W ₄₃₁	W ₄₃₂	W ₄₃₃	W ₄₃₄	W ₄₃₅	W ₄₃₆	W ₄₃₇	W ₄₃₈	W ₄₃₉	W ₄₄₀	W ₄₄₁	W ₄₄₂	W ₄₄₃	W ₄₄₄	W ₄₄₅	W ₄₄₆	W ₄₄₇	W ₄₄₈	W ₄₄₉	W ₄₅₀	W ₄₅₁	W ₄₅₂	W ₄₅₃	W ₄₅₄	W ₄₅₅	W ₄₅₆	W ₄₅₇	W ₄₅₈	W ₄₅₉	W ₄₆₀	W ₄₆₁	W ₄₆₂	W ₄₆₃	W ₄₆₄	W ₄₆₅	W ₄₆₆	W ₄₆₇	W ₄₆₈	W ₄₆₉	W ₄₇₀	W ₄₇₁	W ₄₇₂	W ₄₇₃	W ₄₇₄	W ₄₇₅	W ₄₇₆	W ₄₇₇	W ₄₇₈	W ₄₇₉	W ₄₈₀	W ₄₈₁	W ₄₈₂	W ₄₈₃	W ₄₈₄	W ₄₈₅	W ₄₈₆	W ₄₈₇	W ₄₈₈	W ₄₈₉	W ₄₉₀	W ₄₉₁	W ₄₉₂	W ₄₉₃	W ₄₉₄	W ₄₉₅	W ₄₉₆	W ₄₉₇	W ₄₉₈	W ₄₉₉	W ₅₀₀	W ₅₀₁	W ₅₀₂	W ₅₀₃	W ₅₀₄	W ₅₀₅	W ₅₀₆	W ₅₀₇	W ₅₀₈	W ₅₀₉	W ₅₁₀	W ₅₁₁	W ₅₁₂	W ₅₁₃	W ₅₁₄	W ₅₁₅	W ₅₁₆	W ₅₁₇	W ₅₁₈	W ₅₁₉	W ₅₂₀	W ₅₂₁	W ₅₂₂	W ₅₂₃	W ₅₂₄	W ₅₂₅	W ₅₂₆	W ₅₂₇	W ₅₂₈	W ₅₂₉	W ₅₃₀	W ₅₃₁	W ₅₃₂	W ₅₃₃	W ₅₃₄	W ₅₃₅	W ₅₃₆	W ₅₃₇	W ₅₃₈	W ₅₃₉	W ₅₄₀	W ₅₄₁	W ₅₄₂	W ₅₄₃	W ₅₄₄	W ₅₄₅	W ₅₄₆	W ₅₄₇	W ₅₄₈	W ₅₄₉	W ₅₅₀	W ₅₅₁	W ₅₅₂	W ₅₅₃	W ₅₅₄	W ₅₅₅	W ₅₅₆	W ₅₅₇	W ₅₅₈	W ₅₅₉	W ₅₆₀	W ₅₆₁	W ₅₆₂	W ₅₆₃	W ₅₆₄	W ₅₆₅	W ₅₆₆	W ₅₆₇	W ₅₆₈	W ₅₆₉	W ₅₇₀	W ₅₇₁	W ₅₇₂	W ₅₇₃	W ₅₇₄	W ₅₇₅	W ₅₇₆	W ₅₇₇	W ₅₇₈	W ₅₇₉	W ₅₈₀	W ₅₈₁	W ₅₈₂	W ₅₈₃	W ₅₈₄	W ₅₈₅	W ₅₈₆	W ₅₈₇	W ₅₈₈	W ₅₈₉	W ₅₉₀	W ₅₉₁	W ₅₉₂	W ₅₉₃	W ₅₉₄	W ₅₉₅	W ₅₉₆	W ₅₉₇	W ₅₉₈	W ₅₉₉	W ₆₀₀	W ₆₀₁	W ₆₀₂	W ₆₀₃	W ₆₀₄	W ₆₀₅	W ₆₀₆	W ₆₀₇	W ₆₀₈	W ₆₀₉	W ₆₁₀	W ₆₁₁	W ₆₁₂	W ₆₁₃	W ₆₁₄	W ₆₁₅	W ₆₁₆	W ₆₁₇	W ₆₁₈	W ₆₁₉	W ₆₂₀	W ₆₂₁	W ₆₂₂	W ₆₂₃	W ₆₂₄	W ₆₂₅	W ₆₂₆	W ₆₂₇	W ₆₂₈	W ₆₂₉	W ₆₃₀	W ₆₃₁	W ₆₃₂	W ₆₃₃	W ₆₃₄	W ₆₃₅	W ₆₃₆	W ₆₃₇	W ₆₃₈	W ₆₃₉	W ₆₄₀	W ₆₄₁	W ₆₄₂	W ₆₄₃	W ₆₄₄	W ₆₄₅	W ₆₄₆	W ₆₄₇	W ₆₄₈	W ₆₄₉	W ₆₅₀	W ₆₅₁	W ₆₅₂	W ₆₅₃	W ₆₅₄	W ₆₅₅	W ₆₅₆	W ₆₅₇	W ₆₅₈	W ₆₅₉	W ₆₆₀	W ₆₆₁	W ₆₆₂	W ₆₆₃	W ₆₆₄	W ₆₆₅	W ₆₆₆	W ₆₆₇	W ₆₆₈	W ₆₆₉	W ₆₇₀	W ₆₇₁	W ₆₇₂	W ₆₇₃	W ₆₇₄	W ₆₇₅	W ₆₇₆	W ₆₇₇	W ₆₇₈	W ₆₇₉	W ₆₈₀	W ₆₈₁	W ₆₈₂	W ₆₈₃	W ₆₈₄	W ₆₈₅	W ₆₈₆	W ₆₈₇	W ₆₈₈	W ₆₈₉	W ₆₉₀	W ₆₉₁	W ₆₉₂	W ₆₉₃	W ₆₉₄	W ₆₉₅	W ₆₉₆	W ₆₉₇	W ₆₉₈	W ₆₉₉	W ₇₀₀	W ₇₀₁	W ₇₀₂	W ₇₀₃	W ₇₀₄	W ₇₀₅	W ₇₀₆	W ₇₀₇	W ₇₀₈	W ₇₀₉	W ₇₁₀	W ₇₁₁	W ₇₁₂	W ₇₁₃	W ₇₁₄	W ₇₁₅	W ₇₁₆	W ₇₁₇	W ₇₁₈	W ₇₁₉	W ₇₂₀	W ₇₂₁	W ₇₂₂	W ₇₂₃	W ₇₂₄	W ₇₂₅	W ₇₂₆	W ₇₂₇	W ₇₂₈	W ₇₂₉	W ₇₃₀	W ₇₃₁	W ₇₃₂	W ₇₃₃	W ₇₃₄	W ₇₃₅	W ₇₃₆	W ₇₃₇	W ₇₃₈	W ₇₃₉	W ₇₄₀	W ₇₄₁	W ₇₄₂	W ₇₄₃	W ₇₄₄	W ₇₄₅	W ₇₄₆	W ₇₄₇	W ₇₄₈	W ₇₄₉	W ₇₅₀	W ₇₅₁	W ₇₅₂	W ₇₅₃	W ₇₅₄	W ₇₅₅	W ₇₅₆	W ₇₅₇	W ₇₅₈	W ₇₅₉	W ₇₆₀	W ₇₆₁	W ₇₆₂	W ₇₆₃	W ₇₆₄	W ₇₆₅	W ₇₆₆	W ₇₆₇	W ₇₆₈	W ₇₆₉	W ₇₇₀	W ₇₇₁	W ₇
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EXPERIMENT NO. _____ TITLE Water Injection DATE 3/27/47 SLOAN LABORATORY
 ENGINE CFR 9-B FUEL 73 Octane S.G. .719 WET BULB _____ DRY BULB 77°F
 BORE 3.25" STROKE 4.50" COMPRESSION RATIO 6.0 BAROMETER (ACT.) 760.2 mm Hg (CORR.) 29.825 "Hg

CONSTANTS

BMEP = B.L. X 4245 BHP = B.L. X RPM

REMARKS	TIME RUN	RPM	B. L.	F. L.	TEMP. OIL JAG	OIL PRES.	P _i	P _e	T _i	AIR CONS.	FUEL CONS.	F A	S. A.	Fuel Total	Water Total	Water Cons.	W ₁ x 10 ³	Drift AP	P	Dmp	Emp	Temp	Liquid Cons.	IHP	Is/c	Is/c Is/c																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																											
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EXPERIMENT NO. _____ TITLE Water Injection DATE 4/5/47 SLOAN LABORATORY
 ENGINE CFR 9-B FUEL 73 Octane S.G. .719 WET BULB _____ DRY BULB 74°F
 BORE 3.25" STROKE 4.50" COMPRESSION RATIO 7.0 BAROMETER (ACT.) 771.5 mm Hg (CORR.) 30.270 "Hg

CONSTANTS

BMEP = B.L. x RPM

BHP = B.L. x RPM

REMARKS	TIME RUN	RPM	B.L.	F.L.	TEMP. OIL JAG PRES.	P _i	P _e	T _i	AIR CONS.	FUEL CONS.	F	S.A.	Fuel Ratio	Water Ratio	W _e W _f	Orifice ΔP	R _{ΔP}	B _{mp}	F _{mp}	Imep	Liquid Cons	Inp	Is/c
			"H _g	°F	"Hg	"H _g	"H _g	°F	lb ₃ /sec	lb ₃ /sec	10 ⁻³ /sec	20°C		lb ₃ /sec	lb ₃ /sec	lb ₃ /sec	lb ₃ /sec	psia	psia	psia	lb ₃ /sec		
	1545	1	1300	11.00	142 207 64	1572 162 137		137	.00827	.000418	.06	31	70.0	0	0	3.62	10.55	46.6	25.70	72.3	.498	4.43	.404
	1550	2	1300	12.70	142 208 64	2130 163 140	.00900	139	.00850	.000540	.06	31	72.0	95	.285	5.28	8.97	54.7	26.00	80.7	.825	4.94	.601
	1600	3	1300	14.60	142 206 64	2413 164 139	.01020	142	.00612	.000612	.06	31	76.0	177	.777	1.27	5.46	6.14	62.0	88.5	1.387	5.42	.920
	1605	4	1300	15.00	142 208 64	2543 165 140	.01082	142	.00650	.000650	.06	31	78.0	148	1.065	1.64	6.17	4.84	66.2	26.90	73.1	1.715	5.71
	1620	5	1300	16.30	142 208 65	2681 167 140	.01146	140	.00688	.000688	.06	31	80.0	170	1.285	1.87	6.95	3.46	69.2	27.20	76.4	1.973	5.90
	1630	6	1300	16.40	142 208 65	2811 167 137	.01213	137	.00728	.000728	.06	31	82.0	178	1.367	1.88	7.70	2.16	69.6	27.50	77.1	2.095	5.95
	1640	1	1300	18.0	141 208 66	2763 168 140	.01180	140	.00824	.000824	.07	31	87.0	222	1.875	2.27	7.35	2.64	80.6	28.0	108.6	2.701	6.65
	1650	2	1300	17.7	140 208 66	2657 167 140	.01122	140	.00786	.000786	.07	31	85.0	209	1.712	2.18	6.65	3.70	76.0	27.8	103.8	2.498	6.36
	1660	3	1300	16.7	141 209 64	2535 166 142	.01068	142	.00747	.000747	.07	31	83.0	188	1.473	1.97	5.99	4.92	71.0	27.5	98.5	2.220	6.03
	1655	4	1300	15.8	140 207 64	2413 166 142	.01019	142	.00708	.000708	.07	31	81.0	164	1.125	1.57	5.40	6.14	67.0	27.2	94.2	1.833	5.76
	1655	5	1300	14.9	140 209 64	2277 165 140	.00958	140	.00670	.000670	.07	31	79.0	112	.793	1.093	4.89	7.28	63.2	26.9	70.1	1.403	5.62
	1675	6	1300	13.8	141 208 65	2165 164 140	.00904	140	.00632	.000632	.07	31	77.0	65	.387	.612	4.30	8.62	58.5	26.6	85.1	1.012	5.21
	1625	7	1300	12.8	141 206 64	2018 163 138	.00846	138	.00593	.000593	.07	31	75.0	0	0	0	3.78	10.09	54.4	26.2	80.6	.573	4.94
	1645	1	1300	19.3	141 208 66	2787 168 142	.01180	142	.00946	.000946	.08	31	93.5	212	1.75	1.850	7.35	2.40	82.0	28.1	110.1	2.846	6.75
	1650	2	1300	18.7	141 207 66	2728 168 140	.01150	140	.00920	.000920	.08	31	92.0	203	1.642	1.785	7.00	2.94	79.4	27.9	107.3	2.562	6.58
	1300	3	1300	18.0	140 207 65	2624 167 140	.01104	140	.00884	.000884	.08	31	90.0	182	1.497	1.590	6.46	4.01	76.3	27.7	104.0	2.293	6.37
	1305	4	1300	17.0	140 207 66	2519 166 142	.01054	142	.00844	.000844	.08	31	88.0	157	1.154	1.370	5.91	5.08	72.1	27.4	98.5	1.998	6.10
	1315	5	1300	15.7	141 208 65	2370 165 142	.00994	142	.00796	.000796	.08	31	85.5	115	.760	.955	5.24	6.57	66.6	27.1	93.7	1.556	5.74
	1320	6	1300	14.8	141 210 65	2220 164 140	.00933	140	.00747	.000747	.08	31	83.0	38	.249	.333	4.65	8.07	62.9	26.7	89.6	.946	5.49
	1330	7	1300	14.0	141 210 65	2124 163 138	.00904	138	.00724	.000724	.08	31	82.0	0	0	0	4.33	8.98	59.4	26.4	85.8	.724	5.25

COURSE
GROUP
NAMES

BORE 3.25" STROKE 4.50" COMPRESSION RATIO 7.0 BAROMETER (ACT.) 758.1 mm Hg (CORR.) 29.766" Hg

$$\text{BMFP} = 81 \times 4.245$$

REMARKS	TIME	RUN	RPM	B.L.	F.L.	TEMP.		OIL PRES.	P ₁	P _E	T ₁	AIR CONS.	FUEL CONS.	F/A	S.A.	FUEL/HP	RHC/HP	RHC CONS.	WHP	UNITE/HP	P.	DMEP	FMEP	IMEP	LIT/CONS	IHP	I.S.C.	
						°F	°C																					
	1340	1	1300	22.1	142	205	67	28.57	15.6	136	0.1257	0.00795	.06	31	83.5	136	1352	1.66	8.5	1.2	93.9	28.3	122.2	2.007	9.50	964		
	1345	2	1300	21.3	142	212	67	27.87	15.6	138	0.1220	0.00781	.06	31	82	133	1200	1.64	8.0	1.9	90.5	28.1	118.6	1.931	7.36	945		
	1350	3	1300	20.2	142	207	66	26.77	15.5	138	0.1158	0.00679	.06	31	80	119	962	1.39	7.2	3.0	85.8	27.8	113.6	1.655	6.96	856		
	1355	4	1300	19.0	141	211	66	25.37	15.3	140	0.1070	0.00654	.06	31	78	100	674	1.03	6.4	4.4	80.6	27.45	108.65	1.328	6.62	722		
	1400	5	1300	17.5	141	211	66	23.87	15.3	142	0.1020	0.00612	.06	31	76	69	317	.578	5.6	5.2	74.3	27.10	101.4	92.9	6.21	539		
	1405	6	1300	15.4	141	211	66	22.17	15.2	143	0.0945	0.00576	.06	31	73.5	58.5	234	.414	4.8	7.6	65.4	26.70	92.1	79.9	5.65	509		
	1410	7	1300	13.7	141	211	66	20.07	15.1	142	0.0862	0.00517	.06	31	71.0	12.0	.035	.0676	4.0	9.7	53.9	26.20	80.1	55.2	4.91	465		
	1420	8	1300	11.1	141	211	66	18.18	15.0	143	0.0795	0.00477	.06	31	68.5	0	0	0	0	3.4	10.8	47.1	25.90	73.0	47.7	4.47	388	
	1430	1	1300	22.1	140	211	66	28.27	15.6	138	0.1257	0.00880	.07	31	90.0	125	1062	1.210	8.5	1.5	93.90	28.20	122.10	1.942	7.49	935		
	1440	2	1300	20.9	140	211	66	27.27	15.6	137	0.1187	0.00837	.07	31	87.5	114	884	1.055	7.7	2.5	88.75	27.15	116.70	1.781	7.15	869		
	1450	3	1300	19.9	139	210	66	26.07	15.5	138	0.1133	0.00794	.07	31	85.5	87	503	.634	6.9	3.7	84.50	27.60	112.10	1.277	6.88	679		
	1500	4	1300	18.2	139	211	66	24.57	15.4	138	0.1064	0.00746	.07	31	83.0	64	274	.367	6.1	5.2	77.25	27.30	104.55	1.080	6.35	580		
	1505	5	1300	16.5	139	211	66	22.87	15.3	139	0.0992	0.00695	.07	31	80.5	47	158	.2275	5.3	6.9	70.00	26.90	96.30	85.3	5.94	518		
	1510	6	1300	14.5	141	212	66	21.37	15.1	140	0.0915	0.00641	.07	31	77.5	12	.035	.0576	4.5	8.4	61.50	26.50	88.80	67.6	5.39	451		
	1515	7	1300	13.9	141	211	66	20.37	15.1	140	0.0894	0.00626	.07	31	77.0	0	0	0	0	4.3	8.8	57.00	26.40	85.40	62.6	5.22	432	
	1530	1	1300	22.0	142	212	66	28.37	15.7	137	0.1257	0.00880	.08	31	94.5	120	978	1.210	8.5	1.2	93.4	28.2	121.6	1.982	7.45	958		
	1540	2	1300	20.8	142	212	66	27.37	15.7	140	0.1197	0.00935	.08	31	94.0	104.5	615	.728	7.7	2.4	88.3	28.0	116.3	1.650	7.14	893		
	1545	3	1300	19.6	142	212	66	25.77	15.5	140	0.1133	0.00905	.08	31	91.0	69	317	.350	6.7	3.8	83.2	27.6	110.8	1.222	6.79	699		
	1550	4	1300	17.9	142	207	66	24.57	15.4	140	0.1064	0.00850	.08	31	88.5	50	.177	.208	6.1	5.2	76.0	27.3	103.3	1.081	6.94	584		
	1555	5	1300	15.9	143	207	66	23.01	15.3	141	0.0992	0.00772	.08	31	86.5	14	.037	.047	5.3	6.7	67.5	26.9	94.4	82.9	5.78	515		
	1600	6	1300	15.2	143	207	66	22.37	15.2	142	0.0935	0.00762	.08	31	84.0	0	0	0	0	7.7	7.4	67.5	26.7	96.2	76.2	5.37	492	

EXPERIMENT NO. _____ TITLE Water Injection DATE 4/8/47 SLOAN LABORATORY
 ENGINE CFR 9-B FUEL 73 Octane S.G. .719 WET BULB — DRY BULB 74°F
 BORE 3.25" STROKE 4.50" COMPRESSION RATIO 8.0 BAROMETER (ACT.) 170.1 mm Hg. (CORR.) 30.227 Hg.

CONSTANTS BMEP = B.L. X BHP = B.L. X RPM

REMARKS	TIMER	RPM	B.L.	F.L.	TEMP. OIL °F	JAC.	OIL PSI	P _i	P _e	T _i	AIR CONS.	FUEL CONS.	F	S.A.	Fuel Roto	Water Roto	W _e	Unit ΔP	P _i	BMEP	FMEP	PSIA	PSIA	PSIA	Li % Cons.	I.H.P.	ISIC
			"Hg		°F			"Hg	"Hg	°F	lbs/sec	lbs/sec	1/1000		°C		lbs/sec	W _e	"H ₂ O	ΔP							
	1540	1	1300	8.2	141	210	64	16.6	15.9	140	.00571	.000415	.06	31	65	0	0	0	2.52	13.62	34.8	26.0	60.8	41.5	3.72	402	
	1545	2	"	9.7	138	210	62	18.0	15.9	138	.00750	.000450	"	"	67	16	.158	.351	2.95	12.20	41.2	26.3	67.5	60.8	4.14	530	
	1553	3	"	11.0	143	210	62	18.5	15.9	140	.00807	.000485	"	"	69	74	.452	.932	3.42	10.70	46.7	26.7	73.4	73.7	4.49	752	
	1600	4	"	12.1	143	208	63	21.0	15.9	140	.00863	.000518	"	"	71	98	.633	1.222	3.93	9.21	51.4	27.0	78.4	1151	4.80	819	
	1605	5	"	13.0	142	208	61	22.8	16.0	138	.00926	.000558	"	"	73	136	.885	1.720	4.52	7.87	55.2	27.4	82.6	1.574	5.06	1095	
	1610	6	"	14.8	141	211	62	23.7	16.0	140	.00988	.000593	"	"	75	157	1.147	1.930	5.15	6.49	62.8	27.7	90.5	1.740	5.54	1130	
	1615	7	"	15.9	141	211	61	25.1	16.1	140	.01050	.000631	"	"	77	176	1.412	2.241	5.82	5.04	67.5	28.0	95.5	2.043	5.83	1260	
	1620	8	"	17.2	141	211	62	26.6	16.1	140	.01113	.000669	"	"	79	190	1.587	2.340	6.54	3.85	73.0	28.3	101.3	2.236	6.21	1285	
	1235	1	"	16.5	140	210	65	24.7	16.7	140	.01050	.000736	.07	"	82.5	2.25	1.835	2.470	5.83	5.06	70.0	27.8	97.8	2.571	5.99	1545	
	1235	2	"	15.5	140	210	65	23.8	16.7	140	.00983	.000688	"	"	80	195	1.577	2.300	5.08	6.37	65.9	27.7	93.5	2.275	5.72	1450	
	1240	3	"	14.5	141	210	65	22.5	16.5	140	.00929	.000650	"	"	78	169	1.305	2.010	4.56	7.66	61.5	27.4	88.9	1.935	5.44	1285	
	1245	4	"	13.4	140	211	65	21.0	16.4	140	.00855	.000612	"	"	76	134	.747	1.538	4.01	9.15	56.9	27.0	83.9	1.559	5.13	1080	
	1250	5	"	12.3	140	207	65	18.8	16.4	140	.00822	.000575	"	"	74	97	.616	1.071	3.54	10.37	52.2	26.7	79.9	1.171	4.82	870	
	1300	6	"	11.3	141	211	62	18.7	16.3	141	.00770	.000539	"	"	72	56	.375	.674	3.11	11.50	48.0	26.5	74.5	.894	4.56	688	
	1100	1	"	11.8	144	208	65	18.1	16.3	140	.00796	.000537	.08	"	77.5	0	0	0	3.35	11.42	50.1	26.5	76.6	.637	4.70	488	
	1115	2	"	12.8	141	210	65	20.8	16.3	140	.00895	.000668	"	"	77	57	.358	.533	3.70	10.20	54.3	26.8	81.1	1.024	4.96	744	
	1125	3	"	13.9	141	210	65	21.5	16.4	140	.00935	.000708	"	"	81	102	.659	.930	4.14	9.00	57.0	27.2	86.2	1.366	5.28	931	
	1135	4	"	14.5	141	210	65	22.4	16.5	139	.00935	.000747	"	"	83	164	1.257	1.683	4.40	7.78	61.5	27.4	88.9	2.006	5.44	1325	
	1145	5	"	15.4	141	210	65	23.6	16.5	140	.00989	.000786	"	"	85	205	1.707	2.170	5.12	6.60	65.4	27.7	93.1	2.473	5.70	1570	

COURSE
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NAMES

EXPERIMENT NO. _____ TITLE Alcohol Injection DATE 4/22/47 SLOAN LABORATORY
ENGINE CFR 9-B FUEL 13 Octane S.G. .719 WET BULB _____ DRY BULB 76°F
BORE 3.25 STROKE 4.50 COMPRESSION RATIO 8.0 BAROMETER (ACT.) 166.7 mm. Hg. (CORR.) 30.078" Hg.

[illegible]

XII - APPENDIX - a

After all the data for the water and alcohol injection had been correlated, and the great advantage of alcohol over water was evident from the standpoint of raising the detonation limited IMEP, the thought occurred of trying to inject fuel in the same manner and for the same purpose. On 17 May 1947 a run was made at a compression ratio of 7 and F/A ratio of .07 using 73 octane gasoline as the injected fluid. A series of points was taken and a very favorable comparison obtained of fuel vs. alcohol as an anti-detonator. A thorough investigation of this method of detonation control would be of extreme interest and might lead to results more practical than the use of ethyl alcohol. Certainly the use of one fluid rather than two would facilitate the supply problem and lend itself to a lighter installation; from this standpoint the ideal system would be one in which a single pump would deliver both the primary fuel and the anti-detonating fuel at their optimum timing and through a single line to each cylinder.

XIII - APPENDIX - b

Procedure for Operating C.F.R. Engines

Sloan Laboratory

(1) Preparation:

- (a) Start laboratory gasoline pump.
- (b) Start laboratory exhaust pump.
- (c) Start laboratory trench pump.
- (d) Lock dynamometer cradle.
- (e) Check oil level in engine crankcase.
- (f) Open fuel valve to engine.
- (g) Shut engine fuel pump.
- (h) Open engine ignition switch.
- (i) Open valve to laboratory main exhaust line.*
- (j) Open throttle valve on engine.

(2) Motoring:

- (a) Fill engine jacket.
- (b) Start circulating-water pump.
- (c) Open condenser-coil valve.
- (d) Open exhaust cooling-water valve.
- (e) Close dynamometer main switch.
- (f) Turn field rheostats fully counter-clockwise.
- (g) Close field switch.
- (h) Close armature switch.
- (i) Motor the engine by gradually advancing the starter switch.
- (j) Check oil pressure.
- (k) To adjust rpm after motoring, turn field rheostats.

(3) Firing

- (a) Adjust inlet-air temperature to 100°F.
- (b) Read air consumption.
- (c) Open engine fuel pump. Read fuel consumption. Adjust micrometer to give fuel-air ratio of 0.08 - 0.10 (approx.).
- (d) Close engine-ignition switch.
- (e) To adjust rpm after firing, turn field rheostats.
- (f) To adjust fuel-air ratio, turn fuel pump micrometer.

*Check with all research projects to see if laboratory exhaust and supercharger mains are free for use.

(4) Changing Compression Ratio when Engine is Firing:

- (a) Unlock cylinder-head slightly.
- (b) Turn handle clockwise to decrease compression ratio.
Turn handle counter-clockwise to increase compression ratio.
- (c) Check the desired compression ratio with calibration chart.
- (d) Lock cylinder head.

(5) Stopping:

- (a) Lock dynamometer cradle.
- (b) Adjust to a reasonably low rpm.
- (c) Open engine ignition switch.
- (d) Shut engine fuel pump.
- (e) Close all water valves (important).
- (f) Stop circulating water pump.
- (g) Close fuel valve to engine.
- (h) Open armature switch.
- (i) Open field switch.
- (j) Open dynamometer main switch.
- (k) Close valve to laboratory main exhaust line.
- (l) If no other group is operating engine in the laboratory, close laboratory gasoline pump, exhaust pump and trench pump.

(6) Emergency:

In case of emergency, cut off ignition switch of the engine first. Then follow through the rest of stopping procedure.

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